

Manuscript Number: GEOMOR-8685R1

Title: MIS 9 to MIS 5 terraces along the Tyrrhenian Sea coast of Latium (central Italy): assessing interplay between sea-level oscillations and tectonic movements

Article Type: Review Article

Keywords: paleo-surface; coastal terrace; glacio-eustasy; regional uplift

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Abstract: We present a review of the geomorphology of the Tyrrhenian Sea coast of central Italy integrated by a novel structural-geomorphological study coupled with statistical analysis of topographic culminations and comparison with a Digital Elevation Model, aimed at reconstructing a suite of paleo-surfaces corresponding to remnant portions of marine terraces. We performed geochronological, sedimentological, micromorphological and mineralogical investigations on the deposits forming the different paleo-surfaces between Civitavecchia and Anzio town, in order to provide chronostratigraphical, paleogeographical and paleoenvironmental constraints. Using the newly achieved dataset we correlate these paleo-surfaces with the coastal terraces formed during past sea-level highstands, as recognized by previous studies, and we refine their correlation with the Marine Isotope Stage (MIS) timescale. In particular, we have extended our geomorphological analyses landward in the area between the Tiber River mouth and Anzio, in order to include the oldest paleo-surface developed above the deposits of the last large explosive eruption at 365 ± 4 ka in the Colli Albani Volcanic District. Results of this study allow us to recognize a set of higher paleo-surfaces at elevation ranging 108 to 71 m a.s.l., which we interpret as one tectonically displaced, widespread coastal terrace originated during the MIS 9.1 highstand. We correlate the previously identified paleo-surfaces of 66-62 m and 56-52 m with the equivalent coastal terraces developed during the sea-level highstands of sub-stages 7.5 and 7.3/7.1. Moreover, based on data from literature on relative elevation of maximum sea level during the highstands of MIS 11 through MIS 5.1, we assess the regional uplift and the concurrent tectonic displacements that have occurred since 900 ka in this area.

REVIEWER #1

General points (all language related)

The use and/or omission of articles (definite and indefinite) differs significantly between Italian and English (I know this from a somewhat shaky experience of Italian from evening classes) and I think there are instances in this paper where such English usage is erroneous and requires attention or review. See my annotations but also look carefully at these throughout.

Word choice is often poor, ranging from words that are a bit strange but are understandable (marking the author(s) as writing English as non-first-language user(s)) to words that are simply erroneous. This includes a frequent poor choice of prepositions.

By way of examples, (1) 'superintended' is not a word to use; from the verb 'superintend', it means 'be responsible for the management or arrangement of' (it is commonly used only in the derivative 'superintendent', which is a rank in the police force) and can only be used with reference to people; (2) '...are constituted by ...' is archaic and clumsy English and is a form of words that would be used very sparingly (if at all) by a first-language English writer. It should generally be replaced by 'consist of' or 'comprise'.

The word 'comprised' repeatedly appears in situations where it is superfluous – I have suggested deletion. Your term 'silicoclastic' should be 'siliciclastic', as Google will confirm. Unfortunately, there are several figures that will need correcting, in addition to the text.

We greatly appreciated the careful revision of the English and the precious suggestions provided by the Reviewer, that we have followed throughout.

There are several specialist soil terms used in this paper that may not be readily understood by the typical *Geomorphology* reader (e.g., vertic), although I suppose, like me, they can turn to Google.

The meaning of this word is explained (vertical turnover of soil material). For other specialist terms, see below.

The tenses of verbs are also non-optimal in many cases. I have suggested edited versions.

We thank the reviewer for these edits.

Points of detail:

Line 71 (also in one of the highlights). This is careless wording. The highstands are features of the sea-level record, not the marine-isotope record, as the authors know well enough. The attribution of highstands to particular isotope stages is by means of correlation, helped by the fact that the isotope record is also an archive (indirectly) of palaeoclimate. This passage and the highlight both need rewording.

Sure. We catch the point and agree with it. We have rephrased the sentence.

Line 85. I would query the use of 'the glacial termination IV'. Elsewhere MIS stages have been used, so it is not clear why this is different. Otherwise the system of numbered glacial terminations needs definition – perhaps a table correlating them with the MIS chronology. In terms of English language, I think the definite article (the) should be deleted here.

Ok for the article. We have kept the definition of glacial termination and specified the first time that we mention it that it represents "the onset of sea-level rise during the highstand". This concept is at the base of the methodological approach using the gravel-clay transition in the aggradational succession as a proxy of the sudden ice melting at the end of a glacial period.

Table 1 – some terms used in this table are not recognized and need checking. Please check 'limpid', 'typic', 'disorthic'.

Indeed, vertic, limpid, dishortic and typic are specific terms used in micromorphology. It is a scientific jargon: probably unpleasant, yet correct.

I presume that 'int.' is an abbreviation of 'interference', but this is by no means obvious and should be in full.

ok.

Fig. 13 is an important diagram but is over-reduced, making it difficult to see the subtly different colours (like a high proportion of the male population I have slightly defective colour vision. I would like to see this enlarged and published in landscape format.

We have rotated this figure at 90 degree, in order to have it fitting a full page.

Line 857. This is a rather cryptic statement that needs explanation if it is to mean anything. Do you really mean 'experiments'? This is not very scientific and you leave the reader to guess what the additional insight is. Please tighten this up.

We have rephrased this statement and eliminated the word "experiments". That's indeed a US jargon term for "analyses".

REVIEWER #2

My suggested edits are captured in detail by the numbered comments below.

1) Line 1209: "Facenna et al, 1994c" change with "Facenna et al, 1994"

ok.

2) Figure 1: I suggest adding a dot or a square for the location of Rome and the dash lines (faults) in the alluvial deposits.

ok.

3) Figure 2: the same observation regarding Rome of figure 1; insert also the "north" symbol.

ok.

4) Figure 3: on the contrary of figure 1 the faults are represented with dash line; are they inferred? I suggest to insert the dip for dip slip fault; insert the "north" symbol; draw a line to separate 3a with 3b.

ok.

5) Figs 5-6-7-9a: for a better comprehension I suggest to give a new layout to these figures because there are a lot of information (photo, scheme), but the comprehension is difficult.

We agree that these figures are a bit complicated, but we believe that they contain all the necessary information.

6) Figure 11: insert the graphic scale and "north" symbol.

ok.

9) Figure 16: I suggest to invert the "b¹" with "b" and "b" with "b¹".

ok.

We reconstruct a suite of six paleo-surfaces along the central Tyrrhenian Sea coast

Paleoenvironmental data identify these paleo-surfaces as remnants of coastal terraces

We provide $^{40}\text{Ar}/^{39}\text{Ar}$ age constraints to the terraced sedimentary deposits

We correlate these terraces with the Marine Isotope Stage record

We identify previously unrecognized MIS 9 sea-level markers in this region

We assess regional uplift and tectonic displacements in the last 400 ka

We present a review of the geomorphology of the Tyrrhenian Sea coast of central Italy integrated by a novel structural-geomorphological study coupled with statistical analysis of topographic culminations and comparison with a Digital Elevation Model, aimed at reconstructing a suite of paleo-surfaces corresponding to remnant portions of marine terraces. We performed geochronological, sedimentological, micromorphological and mineralogical investigations on the deposits forming the different paleo-surfaces between Civitavecchia and Anzio town, in order to provide chronostratigraphical, paleogeographical and paleoenvironmental constraints. Using the newly achieved dataset we correlate these paleo-surfaces with the coastal terraces formed during past sea-level highstands, as recognized by previous studies, and we refine their correlation with the Marine Isotope Stage (MIS) timescale.

In particular, we have extended our geomorphological analyses landward in the area between the Tiber River mouth and Anzio, in order to include the oldest paleo-surface developed above the deposits of the last large explosive eruption at 365 ± 4 ka in the Colli Albani Volcanic District. Results of this study allow us to recognize a set of higher paleo-surfaces at elevation ranging 108 to 71 m a.s.l., which we interpret as one tectonically displaced, widespread coastal terrace originated during the MIS 9.1 highstand. We correlate the previously identified paleo-surfaces of 66-62 m and 56-52 m with the equivalent coastal terraces developed during the sea-level highstands of sub-stages 7.5 and 7.3/7.1. Moreover, based on data from literature on relative elevation of maximum sea level during the highstands of MIS 11 through MIS 5.1, we assess the regional uplift and the concurrent tectonic displacements that have occurred since 900 ka in this area.

1 **MIS 9 to MIS 5 terraces along the Tyrrhenian Sea coast of Latium (central**
2 **Italy): assessing interplay between sea-level oscillations and tectonic**
3 **movements**

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17

18 **Abstract**

19 We present a review of the geomorphology of the Tyrrhenian Sea coast of central Italy
20 integrated by a novel structural-geomorphological study coupled with statistical analysis of
21 topographic culminations and comparison with a Digital Elevation Model, aimed at
22 reconstructing a suite of paleo-surfaces corresponding to remnant portions of marine
23 terraces. We performed geochronological, sedimentological, micromorphological and
24 mineralogical investigations on the deposits forming the different paleo-surfaces between
25 Civitavecchia and Anzio town, in order to provide chronostratigraphical, paleogeographical
26 and paleoenvironmental constraints. Using the newly achieved dataset we correlate these
27 paleo-surfaces with the coastal terraces formed during past sea-level highstands, as
28 recognized by previous studies, and we refine their correlation with the Marine Isotope Stage
29 (MIS) timescale.

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31 the Tiber River mouth and Anzio, in order to include the oldest paleo-surface developed
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33 District. Results of this study allow us to recognize a set of higher paleo-surfaces at elevation
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36 paleo-surfaces of 66-62 m and 56-52 m with the equivalent coastal terraces developed during
37 the sea-level highstands of sub-stages 7.5 and 7.3/7.1. Moreover, based on data from
38 literature on relative elevation of maximum sea level during the highstands of MIS 11 through

39 MIS 5.1, we assess the regional uplift and the concurrent tectonic displacements that have
40 occurred since 900 ka in this area.

41

42 **Keywords:** paleo-surface; coastal terrace; glacio-eustasy; regional uplift

43

44 **Highlights:**

45 We reconstruct a suite of six paleo-surfaces along the central Tyrrhenian Sea coast

46 Paleoenvironmental data identify these paleo-surfaces as remnants of coastal terraces

47 We provide $^{40}\text{Ar}/^{39}\text{Ar}$ age constraints to the terraced sedimentary deposits

48 We correlate these terraces with the Marine Isotope Stage record

49 We identify previously unrecognized MIS 9 sea-level markers in this region

50 We assess regional uplift and tectonic displacements in the last 400 ka

51

52

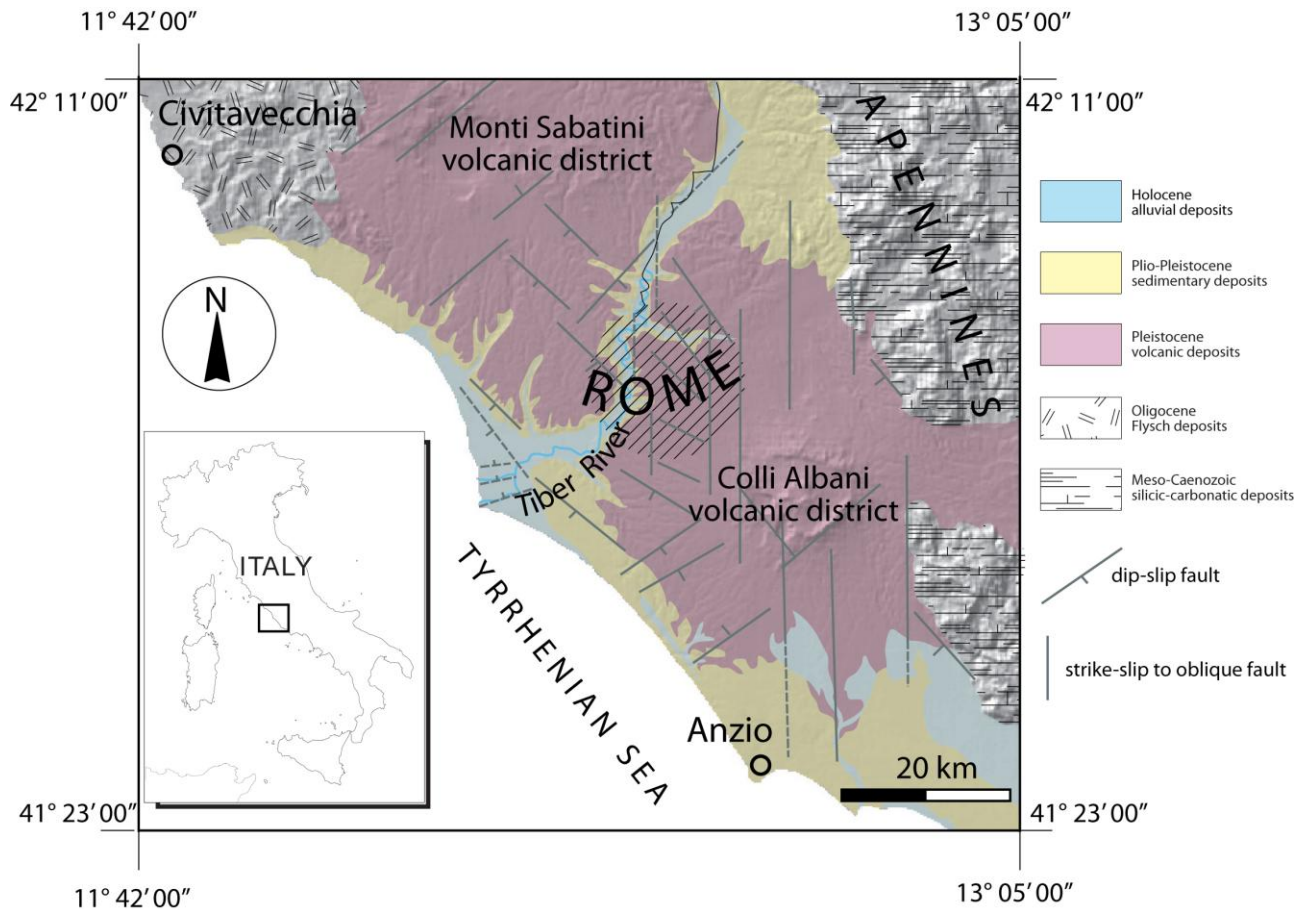
53

54 **1. Introduction**

55 The Tyrrhenian Sea coast of Latium (Figure 1) is part of a geodynamic domain characterized
56 by back-arc extensional processes (Malinverno and Tayan, 1986; Patacca et al., 1990) that
57 during Pleistocene times have led to the formation of an ultra-potassic chain of volcanic
58 districts (Serri et al., 1993; Conticelli and Peccerillo, 1992; Peccerillo and Frezzotti, 2015).
59 Concurrent with the volcanic processes, regional uplift has caused the progressive emergence
60 of this area since the end of the Santernian (lower Calabrian), around 1.5 Ma, leading to
61 widespread continentalization since ~1 Ma (Barberi et al., 1994; Marra et al., 2018a). The
62 regional uplift along the Tyrrhenian coast of Latium has been interpreted as driven by the
63 subduction process and uprising of metasomatized magma bodies on the Tyrrhenian Sea
64 Margin of central Italy, superimposed on a smaller isostatic component of uplift (Marra et al.,
65 2017, and references therein). Two major pulses of uplift are recognized: 0.86 through 0.5 Ma,
66 and 0.25 Ma through the Present (Marra et al., 2016a); as a result of this overall uplifting
67 regime, the continental, fluvial-lacustrine and coastal deposits in this area formed a
68 widespread pattern of terraces that, similar to other regions in the world (e.g., Bridgland and
69 Westaway, 2008), are organized in a staircase geometry, with the oldest surfaces at highest
70 elevation.

71 Geographic extension and rates of the most recent phases of this uplift during Middle-Late
72 Pleistocene have been assessed by a series of studies reconstructing a suite of coastal terraces
73 and correlating them with the sea-level highstands identified by the Marine Isotope Stage
74 (MIS) record (e.g., Karner et al., 2001a; Nisi et al., 2003; Ferranti et al., 2006). More recently, a
75 re-evaluation of the geometry and the age of these terraces in the coastal area between the
76 Argentario and Anzio promontories has been proposed by means of an original
77 geomorphological approach and the integration of new geochronologic constraints provided
78 by $^{40}\text{Ar}/^{39}\text{Ar}$ ages of volcanic layers intercalated within the glacio-eustatically forced
79 aggradational successions forming the terraced deposits in this region (Marra et al., 2015;
80 2016a). Moreover, a new geomorphologic study coupled with biochronologic constraints
81 allowed Marra et al. (2018b, 2019a) to extend the reconstruction of a complete suite of
82 terraces in the coastal reach between Anzio and Circeo promontories, and to propose their
83 correlation with MIS 7.5 through MIS 5.1. In contrast, only a poorly defined paleo-surface
84 ranging 61-67 m a.s.l. has been dubiously assigned to the MIS 9 terrace (Marra et al., 2016a).
85 Moreover, geochronologic constraints so far provided to the local MIS 9 aggradational
86 succession (Aurelia Formation, Karner and Marra, 1998) evidenced a remarkable anomaly,
87 significantly pre-dating glacial termination IV and the completion of MIS 9 highstand (Marra

88 et al., 2016b). Therefore, assessing the geometry and providing time constraint on the
 89 deposits of the MIS 9 coastal terrace in this region may have notable implications for
 90 understanding the response to the global paleo-climatic signal and on the tectonic process
 91 acting on the Tyrrhenian Sea margin of central Italy.



92
 93 Figure 1 - DEM image of the Tyrrhenian Sea margin of central Italy showing the main
 94 structural features of the investigated area (after Acocella and Funicello, 2006; Frepoli et al.,
 95 2010).
 96

97 In the present paper we have refined the structural-geomorphological study in the previously
 98 investigated sector comprised between Civitavecchia and Anzio, and we have re-assessed the
 99 statistical analysis of the elevations of the paleo-surfaces correlated by Marra et al. (2016a,
 100 2019a) with the MISs. In particular, we have extended the geomorphological analysis
 101 landward, in order to include the oldest paleo-surface affecting the deposits of the last large
 102 eruption in the Colli Albani Volcanic District (Villa Senni Eruption Cycle, 365±4 ka, Marra et
 103 al., 2009) in the area between the Tiber mouth and Anzio. Two huge pyroclastic-flow deposits
 104 emplaced during this eruption phase (Tufo Lionato and Pozzolanelle, Freda et al., 1995)
 105 mantle the surface with a volcanic cover spreading radially as far as 50 km from the vent and
 106 reaching up to 20 m in thickness, locally (De Rita et al., 1995; Giordano et al., 2006; Mariucci

107 et al., 2008). Due to this pyroclastic cover, the paleo-surfaces older than 365 ka are completely
108 buried and no geomorphologic evidence is expected for them in this area.

109 We performed chronostratigraphical, sedimentological, micromorphological, mineralogical
110 and petrographic investigations of the deposits forming the different paleo-surfaces in order
111 to provide geochronological, paleogeographical and paleoenvironmental constraints. We used
112 four $^{40}\text{Ar}/^{39}\text{Ar}$ age determinations on detrital sanidine crystals extracted from key deposits in
113 order to provide post-*quem* ages on the paleo-surfaces and relative chronologic constraints
114 for their correlation with the suite of coastal terraces recognized and geochronologically
115 constrained by previous studies, refining their correlation with the MIS timescale.

116

117 **2. Geological Setting**

118 The study area is located on the Tyrrhenian Sea margin of central Italy (Figure 1).
119 Since the Middle Pleistocene the interplay between glacio-eustatic sea-level variations,
120 tectonic processes, sedimentation and volcanic activity has built the geological framework of
121 this area (Luberti et al., 2017, and references therein). During periods of sea-level fall, erosion
122 occurred, whereas deposition took place during phases of sea-level rise, filling previously
123 excavated incisions with a suite of aggradational successions (Karner and Marra, 1998; Marra
124 et al., 2008). A thick succession of pyroclastic-flow deposits, from both the Colli Albani and
125 Monti Sabatini volcanic districts, and subordinated Sabatinian air-fall deposits, interfingers
126 with the continental sediments. After the last volcanic eruptions at 36 ka (Marra et al., 2016c),
127 the volcanic plateau was deeply incised during the Last Glacial, partly as a consequence of the
128 intervening regional uplift (Marra et al., 2016a). Eventually, the paleovalleys were filled by
129 fluvial deposits as a consequence of the sea-level rise after the last glacial termination.

130

131 **3. Methods**

132 **3.1 Geomorphological analysis**

133 In the present study, paleo-surfaces have been mapped following the geomorphological
134 approach described in Marra et al. (2016a; 2017), based on the identification of a set of flat
135 surfaces characterized by topographic culminations with elevation ranging through a few
136 meters around a mean value. Selected topographic culminations of the reconstructed paleo-
137 surfaces were detected on Istituto Geografico Militare 1:25.000 topographic maps of Italy.
138 They include all the hilltops (i.e., each elevation point within a closed, 5 m interval contour
139 line, represented by upward triangles in the figures of this work) and other quasi-equivalent
140 points within plateau-like sectors (downward triangles). The identification of the paleo-

141 surfaces is based on a combined approach that integrates statistically significant
142 concentrations of elevations around a mean value, and the morphologic evidence for the
143 concentration of these elevation points within a finite area, as detected in the maps (see
144 Marra et al., 2016a for detailed methodology). The full dataset of topographic elevations is
145 reported on the scanned 1:25.000 topographic maps and provided as Supplementary Material
146 #1.

147 Distribution of the topographic culminations has been statistically analyzed in order to verify
148 the occurrence of discrete elevation intervals corresponding to peaks of concentration, which
149 can be assumed to be the mean level for each paleo-surface. Comparison between the
150 complete dataset of elevation points (hilltops + plateaux) and that represented only by hilltop
151 elevations has been also provided, to highlight possible subjective selection of the plateau-like
152 culminations and to exclude biases.

153 Finally, a set of elevation ranges defining the principal paleo-surfaces identified using the
154 described geomorphological method has been mapped through DEM analyses, to compare the
155 results.

156

157 **3.2 DEM analysis**

158 Five classes of elevations highlighted by the geomorphological study have been mapped using
159 an interferometric Digital Elevation Model (DEM) with a ground resolution of 30 meters (1
160 arcsec) derived from the NASA SRTM mission (<http://www2.jpl.nasa.gov/srtm>, Farr et al.,
161 2000). When the overall topographic relief of the Italian peninsula is considered, the DEM
162 shows an averaged altitude accuracy of ~15 meters, but in our case, considering areas quite
163 close to the sea and showing low altitude ranges (i.e., 0 - 120 m), the accuracy is one order of
164 magnitude better, and can be estimated in 1-2 m.

165 The analysis was performed entirely within a GIS environment. Initially, the DEM was
166 delimited on the basis of the study area using a polygon shapefile, then the various classes
167 were identified one by one, generating 5 different layers. Five queries were applied to the
168 DEM, each time considering the maximum and minimum values of each class so as to isolate
169 the desired altitude interval. Finally, the layers were merged into a single one and symbolized
170 with 5 different colors, one for each class.

171

172 **3.3 Micromorphological analyses**

173 Three undisturbed soil samples (TML-CC, VDT, VOC) and three loose sand samples (TML-SA,
174 PC-SA, CSR-SA) have been studied in thin sections for micromorphological analysis and for

175 sand mineralogy determination, respectively, aimed at investigating the pedological and/or
176 sedimentological features, and to recognize the origin of the deposit forming the
177 corresponding paleo-surface. One sediment sample collected from the paleo-surface ranging
178 60-67 m (CR1) in the northern sector was analyzed by Villa et al. (2018), and the results are
179 reported here to integrate with the dataset above.

180 Descriptions of thin sections are summarized in Table 1, results of the petrographic
181 determination of sand grains are reported in Table 2. Methods and microphotographs of thin
182 sections for micromorphological analyses are provided in Supplementary File #2A.

183

184 **3.4 Mineralogical analyses**

185 Fifteen samples collected close to the top, and in some instances at increasing depth, on the
186 different paleo-surfaces (VL-1, VL-2, MM, VCR-1, VCR-2, VCR-3, TB-1, TB-2, TB-3, VVL, TML-
187 SA, TRIG, VDT, SPR, RUT), and three sediment samples (RSC, CDC, CR-1), have been analyzed
188 by X-rays diffraction and with a scanning electron microprobe (SEM) in order to describe
189 their mineralogy and texture.

190 Methods, microphotographs and full-resolution diffractograms are provided in
191 Supplementary File #2B-C.

192

193 **3.5 $^{40}\text{Ar}/^{39}\text{Ar}$ dating**

194 Sanidine crystals were extracted from four samples of sediment to provide terminus post-
195 quem ages to the time of deposition of the terrains and/or the accretionary soils forming the
196 paleo-surfaces ranging 98-108 m (TML-SA), 71-79 m (RSC-SA), 60-67 m (CR-3), 51-57 m
197 (CSR-SA) a.s.l., in the area between the Tiber mouth and Anzio. Sampling locations are shown
198 in Figure 3.

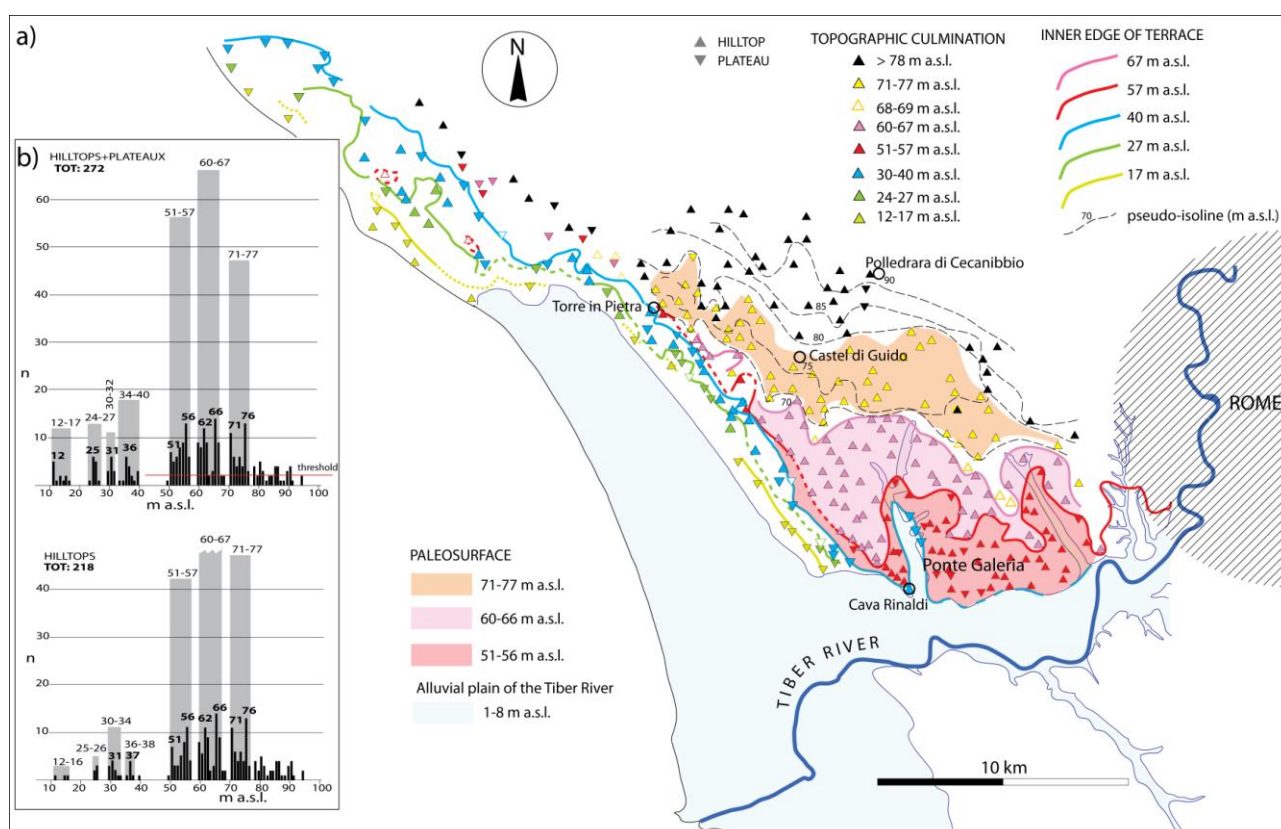
199 Sanidine phenocrysts were co-irradiated with the 1.1864 Ma Alder Creek sanidine standard
200 (Jicha et al., 2016; Rivera et al., 2013) at the Oregon State University TRIGA reactor in the
201 Cadmium-Lined In-Core Irradiation Tube. Single crystal fusion analyses were performed at
202 the WiscAr laboratory at the University of Wisconsin-Madison using a 60W CO₂ laser and a
203 Noblesse multi-collector mass spectrometer following Jicha et al. (2016). Results are reported
204 in Table 4. Full analytical data are reported in Supplementary Material #3.

205

206 **4. Results**

207 **4.1 Geomorphological analysis**

208 Results of the geomorphological study performed for the present work in the coastal area
 209 between Civitavecchia and Anzio are in good agreement with those previously obtained by
 210 Marra et al. (2016a, 2019a). We have statistically re-analyzed hilltops and plateaux elevations
 211 separately, in the two coastal sectors north and south of the Tiber mouth. Very similar
 212 statistical assessment for the elevation ranges of the detected paleo-surfaces have been
 213 obtained for the two sectors, which are reported in Figure 2 and 3, respectively. In these
 214 figures, all the topographic culminations identified on the 1:25.000 maps are indicated with
 215 triangles of different colors. In the northern sector, each color is associated with an elevation
 216 range defining a paleo-surface which, in turn, is established from the statistical analysis.
 217 Elevation ranges for the paleo-surfaces are represented by grey boxes of cumulative
 218 frequency above a threshold value of $n=2$ for a total number of data >20 (red horizontal line
 219 in Figure 2b), while continuous distributions are considered for classes of $n < 20$. Open
 220 triangles are used for hilltops whose elevation is not statistically significant and are not
 221 associated with a paleo-surface. These elevations are interpreted as reflecting topographic
 222 culminations that represent eroded higher rank paleo-surfaces; for this reason, the same color
 223 used for the corresponding pristine paleo-surface is also used for these triangles.



224
 225 Figure 2 - Geomorphological map (a) and topographic culmination statistics (b) in the
 226 northern sector between Civitavecchia and the Tiber mouth. Elevations of topographic
 227 culmination are omitted for clarity in this figure and can be found in Suppl. Mat. #1A. See text
 228 for comments.

232 Figure 3 - Geomorphological map (a) and topographic culmination statistics (b) in the
233 southern sector between the Tiber mouth and the Anzio promontory. Elevations of
234 topographic culmination are omitted for clarity in this figure and can be found in Suppl. Mat.
235 #3. See text for comments.
236

237 A similar approach is used in the southern sector where, due to the larger number of data, a
238 threshold value of $n=5$ is established to define the classes of elevation for all the paleo-
239 surfaces except the lowest two (Figure 3b). Moreover, in a few cases the elevation range for
240 each color is slightly larger than the mean elevation range (grey boxes) established for the
241 paleo-surfaces based on histograms, in order to include all topographic points.

242 Color shading is used in Figure 2 for three oldest paleo-surfaces which have a wider extent
243 and are located inland, while inner margins are represented by solid colored lines for the
244 paleo-surfaces stretching along the coast, which are assumed to represent coastal terraces.
245 Different shades of the orange color are used in Figure 3 to highlight the highest paleo-
246 surfaces that are located inland which, according to discussion in the following sections, are
247 interpreted as having the same age, whereas inner terrace margins are reported for the
248 youngest paleo-surfaces along the coast.

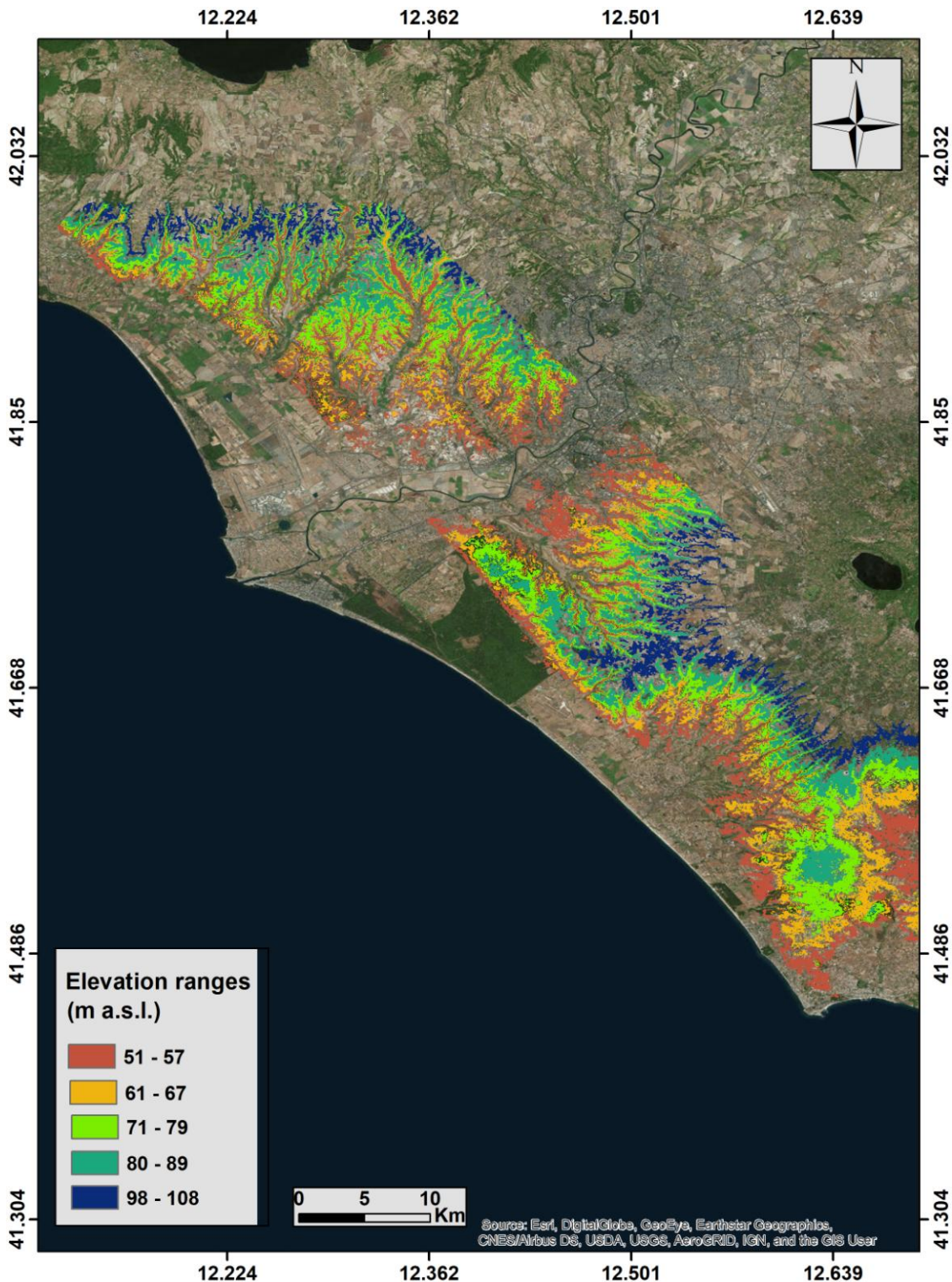
249 In both sectors illustrated in Figures 2 and 3, three lowest orders of terrace are identified by a
250 series of topographic culminations, each one providing well-clustered, distinct elevation
251 ranges, which define three paleo-surfaces narrowly elongated parallel to the coast. The lowest
252 paleo-surface ranges 12-17 m a.s.l., with a peak at 12 m (Figure 2b), and 12-18 m a.s.l., with a
253 peak at 16 m (Figure 3b), in the northern and in the southern sector, respectively. A second
254 paleo-surface has very narrow ranges of 24-27 and 22-27 m a.s.l., with peaks at 25 and 26 m,
255 in the northern and in the southern sector, respectively.

256 A third, higher paleo-surface is characterized by a wider range of elevations, with a main
257 concentrations between 34-40 and 34-43 m a.s.l. in the northern and southern sector,
258 respectively, and with a minor peak at 31 m, in both sectors.

259 A fourth, wide paleo-surface is that ranging 51-57 m a.s.l. and characterized by two relative
260 maxima at 51 and 56 m, in both sectors. Another two well-defined elevation ranges of 60-67
261 m, and of 71-77 m, are clearly identified in both sectors, and are associated with fifth and sixth
262 paleo-surfaces, respectively.

263 Finally, two more concentrations of elevation values, peaking at 80-86 and 101-105 m a.s.l.,
264 define the two highest paleo-surfaces on the inland coastal sector south of the Tiber mouth,
265 whereas in the northern sector topographic culminations show progressively increasing
266 elevation inland, without any apparent clustering around a mean value.

267 Comparison of the results of the geomorphological study with the DEM of Figure 4 shows a
268 very satisfactory match. In particular, we note the close correspondence between the
269 geometrical patterns defined by the 51-57 m paleo-surface in the geomorphological maps of
270 Figure 2 and 3, and in the DEM image of Figure 4 (represented by the red color in both
271 representations), as well as, between those pertaining to the highest paleo-surface of 98-108
272 m (represented by the deep orange color in Figure 3 and by the deep blue color in Figure 4).



274 Figure 4 - Interferometric Digital Elevation Model (DEM) mapping of the five classes of
 275 elevations highlighted by the geomorphological study.
 276

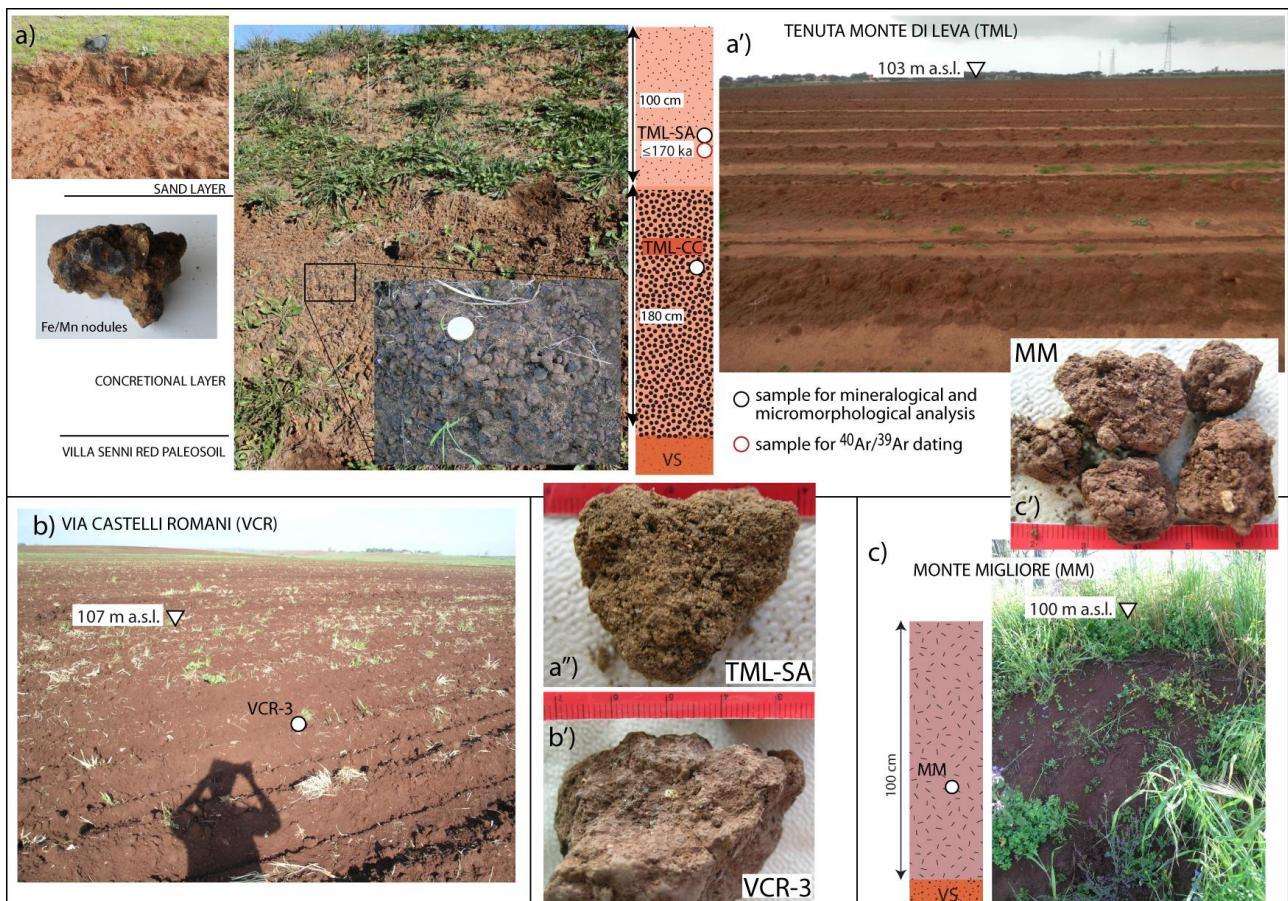
277

278

279 4.2 Stratigraphic investigations

280 4.2.1 Paleo-surface 98-108 m a.s.l.

281 Exposure of the sedimentary deposits forming the highest paleo-surface in the investigated
 282 area is provided by a road cut in Tenuta Monti di Leva (TML), at km 27 of Via Pontina (Figure
 283 5a, see Figure 3 for location). Here, a pedogenically modified horizon occurs in the upper 100
 284 cm and is constituted by fine to medium sized sand in silty-clayey matrix, orange in color
 285 (Figure 5a-a"). A 180 cm thick concretionary layer, constituted by aggregated, cm-sized Fe
 286 and Mn nodules within a sand matrix, occurs at the bottom of this horizon and overlies a red
 287 paleosol developed on top of the pyroclastic-flow deposit of Pozzolanelle (Villa Senni Eruption
 288 Cycle, 365±4 ka; Freda et al., 1997; Marra et al., 2009). A sample of the upper sand layer
 289 (TML-SA) and another from the concretionary layer (TML-CC) were analyzed for mineralogy
 290 and micromorphology, respectively. Forty-one sanidine crystals extracted from sample TML-
 291 SA were dated by the $^{40}\text{Ar}/^{39}\text{Ar}$ method.



292

293 Figure 5 - Photographs and stratigraphic schemes showing the 98-108 m a.s.l. paleo-surface
294 and the sections from which samples analyzed in the present study were collected. See text
295 for comments.
296

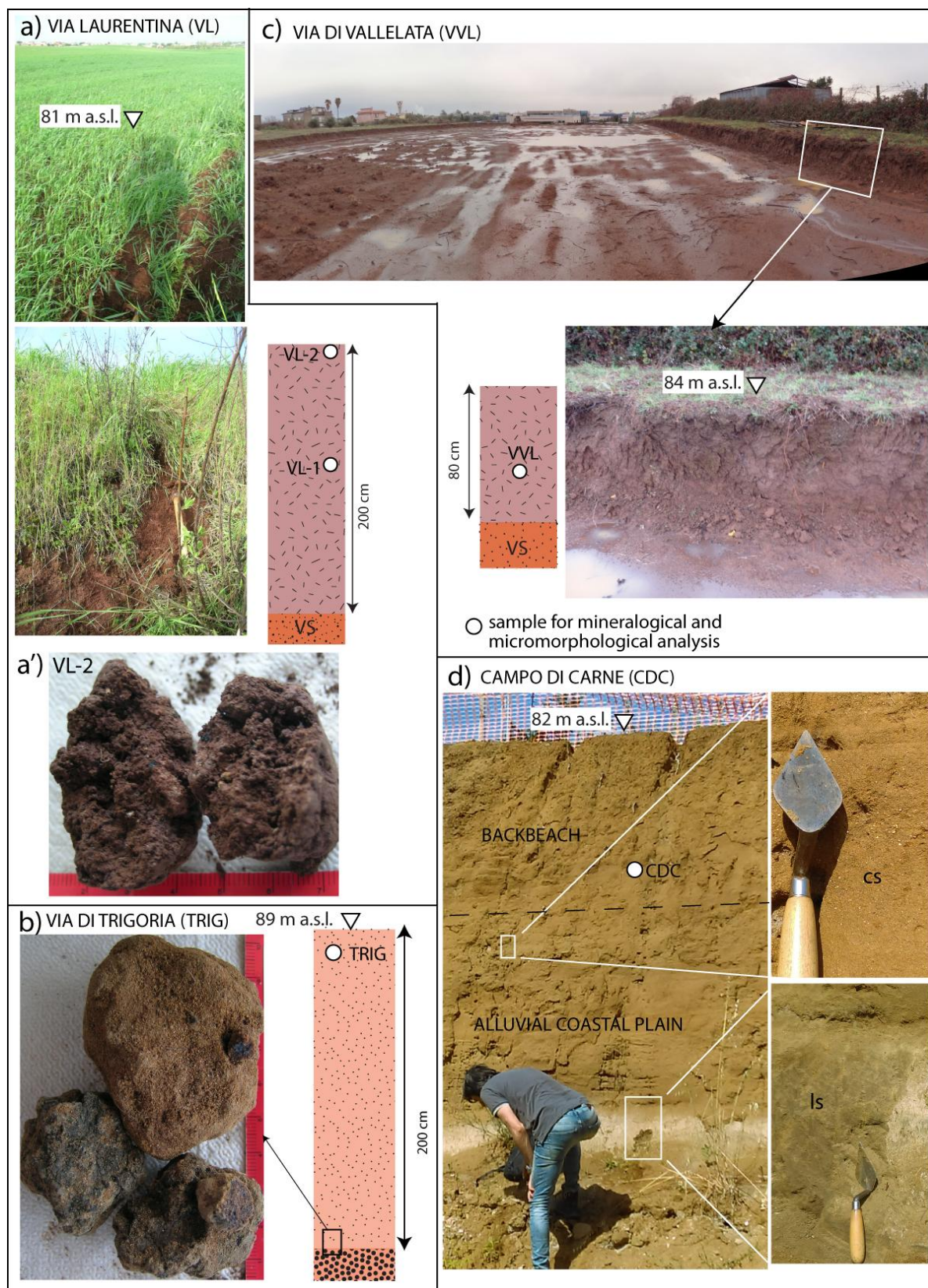
297 The Tenuta Monte di Leva paleo-surface is affected by intensive ploughing which exposes
298 shreds of the upper, orange sand layer, allowing recognition of the presence of this
299 sedimentary deposit throughout the sector crossed by the Pontina Road between km 27 and
300 km 25 (see Figure 3a). A similar in color, but finer sandy-clay deposit is exposed by plowing
301 grooves on top of this highest paleo-surface, further inland. Four samples were collected
302 along the Via dei Castelli Romani and Via Laurentina, at increasing distance inland, with
303 respect to the Tenuta Monte di Leva site (Figure 3). Three samples (VCR 1-3) were collected
304 at elevations between 105 and 107 m a.s.l. in the fields exposing clods of the sub soil (Figure
305 5b). Although the direct contact is not exposed in this flat sector, a geologic substrate
306 represented by the Pozzolanelle pyroclastic-flow deposit (hereby PL) is visible in the scanty
307 outcrops along the stream incisions at its margin. A fourth sample (MM) was collected at the
308 Monte Migliore-La Selvotta locality, at 100 m a.s.l., from the middle of a 100 cm thick, dark red
309 paleosol developed above the PL, exposed by a road cut (Figure 4c). A larger amount of clay
310 matrix, dark red in color, characterizes the samples collected in these inland sectors of the 98-
311 108 paleo-surface (VCR 1, 2, 3, MM, Figure 5b'-c'). Frequent pyroxene crystals and sparse,
312 altered volcanic scoriae 1 to 5 mm in size, are embedded in the clay matrix of these soils,
313 evidencing an at least partial origin from the directly underlying volcanic deposit.
314 Two more samples were collected in a later time at higher elevation, in the area inland with
315 respect to that pertaining to the 98-108 paleosurface (SPR at 139 m a.s.l.) and with respect to
316 the narrow alignment of topographic culminations ranging 100-110 m in the more southern
317 sector (RUT at 125 m a.s.l.) (Figure 3), aimed at investigating the origin of the abundant silico-
318 clastic fraction highlighted by micromorphologic and petrographic analyses in the soils
319 developed above the volcanic substrate.

320

321 **4.2.2 Paleo-surface 80-89 m a.s.l.**

322 Different fragments of this paleo-surface are identified northwest and southeast of the highest
323 sector corresponding to the 98-108 paleo-surface (Figure 3). As for the latter, the 80-89
324 paleo-surface is also developed above different geologic substrates as a function of the
325 distance from the coastline: above the PL in the inland sectors, and above sedimentary sand
326 deposits to the southwest. Five samples were collected in the different sectors of this paleo-
327 surface. Two samples (VL-1, VL-2, Figure 6a) were collected in the middle and at the surface

328 of a thick paleosol developed above the PL in Via Laurentina, in the inland margin of the
 329 northernmost stretch of this paleo-surface. A further sample (TRIG, Figure 6b) was collected
 330 at its opposite, seaward extreme, on the ground surface in a sandy deposit (Figure 3).



332 Figure 6 - Photographs and stratigraphic schemes showing the 80-89 m a.s.l. paleo-surface
333 and the sections from which samples analyzed in the present study were collected. See text
334 for comments.

335
336 This sedimentary deposit is quite similar to that cropping out in Tenuta Monte di Leva (TML):
337 it is a medium-to-fine grained, orange sand in a sparse clay matrix, without sedimentary
338 structures, ca. 3 m thick (Figure 6b). At the base of the exposed section a concretionary layer
339 rich in Mn/Fe nodules, quite similar to that occurring in TML, is present.

340 A fourth sample (VVL, Figure 6c) was collected in the middle of an ca. 80 cm thick paleosol
341 developed above the PL in Via Vallelata, in the inland margin of the southernmost stretch of
342 the 80-89 m paleo-surface (Figure 3). This reddish soil, like the thicker soil sampled in Via
343 Laurentina (Figure 6a'), consists of very fine, clayey sediment containing abundant
344 pyroxene crystals and altered volcanic scoriae, and appears quite similar to the other soils
345 developed directly above the PL sampled for this study.

346 Finally, one sample (CDC) was collected in Campo di Carne in a road excavation exposing a ca.
347 3 m thick deposit constituting of fine, faintly bedded sand in a sparse clay matrix, with dm-
348 thick layers of coarse sand (cs in Figure 6d), whose top at 82 m a.s.l. is part of the seaward
349 portion of the 80-89 m a.s.l. paleo-surface. A layer of dark, greenish loamy fine sand, ca, 60 cm
350 thick, occurs at the base of the exposed section in CDC (ls in Figure 6d).

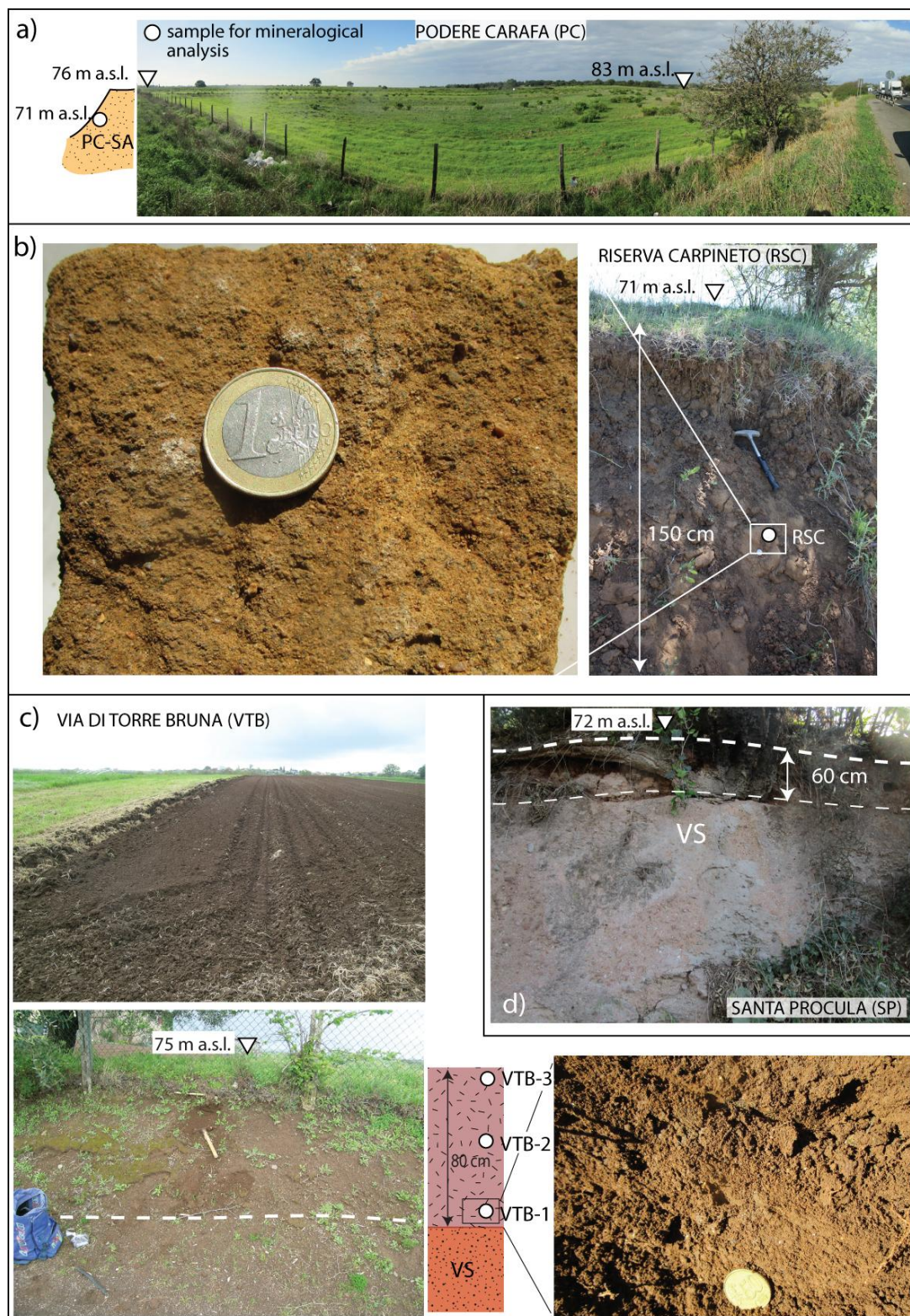
351

352 **4.2.3 Paleo-surface 71-79 m a.s.l.**

353 Two particularly level, small sectors at elevations around 76 m a.s.l. can be detected in the
354 northern and southern margins of the investigated area, in the Podere Carafa (PC) and
355 Riserva Carpineto (RSC) estates (Figure 3). In the PC, an almost perfectly flat area (Figure 7a)
356 is truncated by a sharp scarp to the southwest, dividing it from another level area at ca. 56 m
357 a.s.l. (Castel Romano -CSR), while it connects more gently to a slightly higher sector,
358 corresponding to the 80-89 paleo-surface, to the northeast. A marked fluvial incision
359 dissecting the plateau exposes the terrains forming the 71-79 m paleo-surface, showing
360 massive sand deposit of at least five meters thickness, where sample PC-SA analyzed during
361 this study was collected (Figure 7a).

362 A remarkably similar geomorphologic and stratigraphic setting is observed at the RSC. Here a
363 wide level area at elevations ranging 70-79 m is intensely dissected by steep stream valleys,
364 and almost without geomorphologic break connects with another large area to the southeast,
365 including the Campo di Carne (CDC) site, at an elevation between 80 and 85 m a.s.l. (Figure 3).
366 A massive, medium to coarse sand deposit with sparse, well-rounded fine gravel (sample RSC,

367 Figure 7b) constitutes the geologic substrate in this area, and directly overlies the lower flow
 368 unit of the Villa Senni eruption cycle (Tufo Lionato).



369
 370 Figure 7 - Photographs and stratigraphic schemes showing the 71-79 m a.s.l. paleo-surface
 371 and the sections from which samples analyzed in the present study were collected. See text
 372 for comments.
 373

374 A portion of this 71-79 m a.s.l. paleo-surface also occurs within the structurally controlled
375 sector of Ardea, bordered by the NE-SW trending normal faults of the Ardea Basin (Figure 3).
376 This is a half-graben which originated as a transversal Tyrrhenian Sea basin in Lower
377 Pleistocene times, as evidenced by off-shore seismic lines (Faccenna et al., 1994). The
378 continued Middle Pleistocene activity of these faults is suggested by the marked control on
379 the paleo-coastlines, testified by the geometry of the inner edges of the MIS 7 and MIS 5
380 terraces reconstructed in Marra et al. (2016a, 2019a) and shown by our refined study in
381 Figure 3 and in Figure 4.

382 In contrast to the more seaward sectors, here the 71-79 paleo-surface is developed upon the
383 PL (Figure 7c-d), and characterized by a shallow, 60-80 cm thick, dark brown paleosol. Three
384 samples have been vertically sampled in this paleosol at the Via di Torre Bruna (VTB 1-3,
385 Figure 7c).

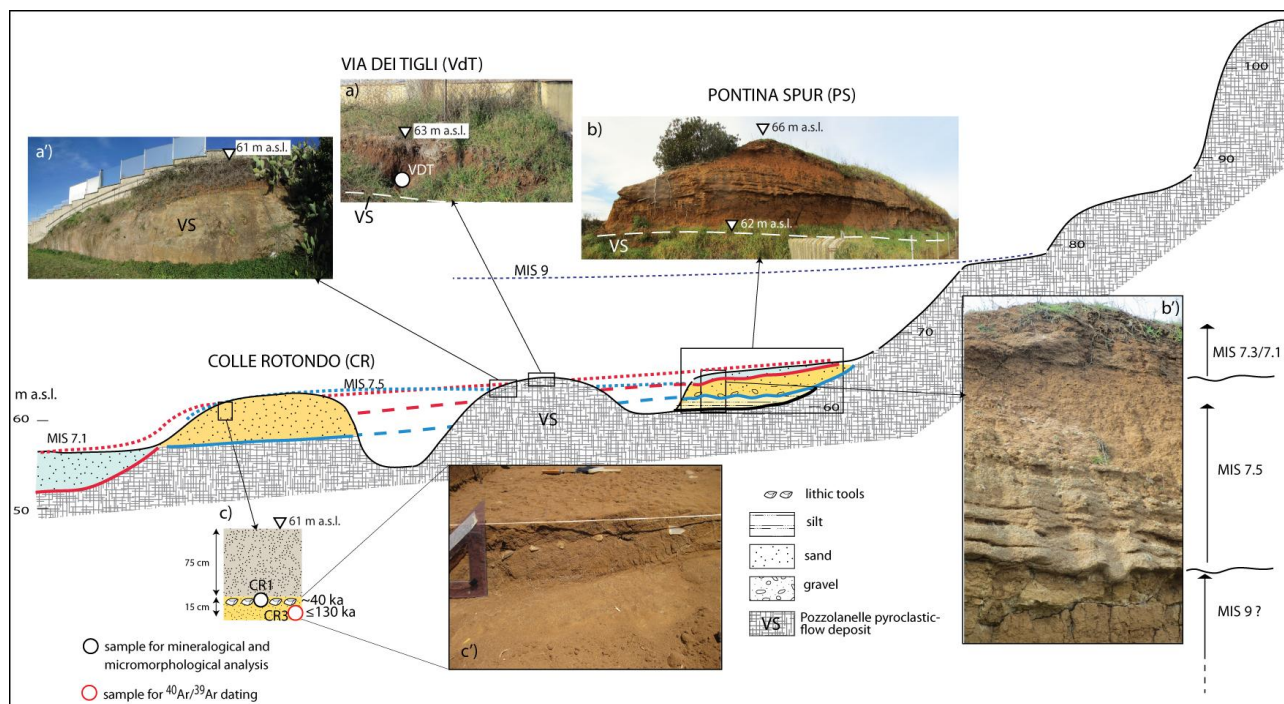
386 Figure 2 shows a wide 71-77 m paleo-surface that we have reconstructed in the coastal sector
387 north of the Tiber mouth (Ponte Galeria area), which in Marra et al. (2016a) was not
388 highlighted. However, scanty sedimentary deposits occur at these elevations in this area,
389 where the outcropping terrains are mostly represented by the Monti Sabatini volcanic
390 succession. Notably, thin layers of calcareous lacustrine muds, ca. 50 m thick, crop out at 72 m
391 a.s.l. in Castel di Guido, and are overlain by the pyroclastic-flow deposit of Tufo Giallo di
392 Sacrofano (285 ± 2 ka, Karner et al., 2001b; Sottili et al., 2010), which forms most of the
393 hilltops of the 71-77 m paleo-surface (Marra et al., 2018c). We interpret these sedimentary
394 strata as the remnants of an alluvial coastal plain, mantled by a thin cover of pyroclastic
395 deposits.

396

397 **4.2.4 Paleo-surface 61-67 m a.s.l.**

398 No evident paleo-surface is associated with this class of elevations in the sector south of the
399 Tiber mouth, except that pertaining to small, isolated plateaux, like at the Colle Rotondo
400 locality (CR, Figure 8). The Colle Rotondo site is located on the flat surface of an E-W
401 elongated hill, culminating 63.5 m a.s.l., bordered by the steep flanks of two convergent
402 streams, 2.5 km east of the present coast, and 7.5 km north of Anzio (Figure 3). This is part of
403 a series of hilltops ranging 61-67 m a.s.l., aligned along a narrow stripe of land defining a
404 coastal terrace between Ardea and Anzio (pink triangles in Figure 3). This terrace is shifted
405 inland, significantly, within the Ardea basin, paralleling the behavior of the inner edge of the
406 51-57 m terrace, as well as that of the two lower terraces of 34-43 m, and 22-27 m (Figure 3).
407 Notably, in the coastal sector overlooking the most elevated area of TML, corresponding to the

408 98-108 m paleo-surface, only plateau points define the 60-67 m terrace, while almost no
 409 evidence of the 51-57 m terrace occurs in the coastal reach north of the Ardea basin,
 410 consistent with erosion due to tectonic uplift of this sector. In contrast, a well-defined 60-67
 411 m terrace occurs at the northwestern margin of the lower area represented in Figure 3, facing
 412 the terminal reach of the Tiber Valley.



413
 414 Figure 8 - Composite cross-section, constructed by projecting the Colle Rotondo (CR) site on
 415 an ideal profile passing by the Santa Procula (SP), Pontina Spur (PS), and Via dei Tigli (VdT)
 416 sites (see Figure 3 for location), aimed at showing the stratigraphic relationships between the
 417 sedimentary successions underlying the 60-67 m a.s.l. paleo-surface.

419 A pedogenized surface horizon consisting of brown sandy silt, heavily disturbed by ploughing,
 420 occurs in the upper 75 cm at CR (Figure 8c). It overlies a reddish-brown silty sand horizon,
 421 incorporating mm-sized Mn and/or Fe concretions (Figure 8c'). A large number of stone
 422 artifacts attributed to the Uluzzian culture (45-41 ka) was found within the upper portion of
 423 this sand layer, ranging in thickness from 6 to a maximum of 20 cm (Villa et al., 2018). One
 424 sand sample (CR1) collected within the archaeological layer was analyzed for
 425 micromorphology by Villa et al. (2016), while 39 sanidine crystals extracted from a sand
 426 sample (CR3) collected immediately below (see Figure 8c) have been dated as part of the
 427 present work.

428 A different geologic substrate characterizes the 60-67 m paleo-surface at two sites located in
 429 the northern portion of the Ardea Basin, Via dei Tigli (VdT) and Pontina Spur (PS) (Figure 3).

430 A ca. 80 cm thick, brown-reddish clayey paleosol overlies the PL at VdT (Figure 8a). Field
431 surveys showed that the substrate of the 60-67 m paleo-surface in this area is represented by
432 a pedogenized layer on top of the PL (e.g., Figure 8a'). One sample from this soil (VdT) has
433 been analyzed for micromorphology.

434 A peculiar situation is observed at PS, where two fining-upwards successions overlie a third,
435 faintly bedded fine sand deposit, which in turn overlies the PL (Figure 8b-b'). The two upper
436 successions consist of a basal gravel layer, made up of reworked volcanic material with
437 characteristic, large leucite crystals turned into analcime, suggesting provenance from the PL
438 (Freda et al., 1997). The finer, upper part is also made up largely of volcanic sand. Both have
439 evident fluvial origin. The lowest layer is a silty fine sand, of possible palustrine or alluvial
440 origin. No sample was collected from this section, due to its very local significance, while a
441 correlation with the other sections of the 60-67 m paleo-surface and a paleoenvironmental
442 interpretation is provided in the cross-section of Figure 8.

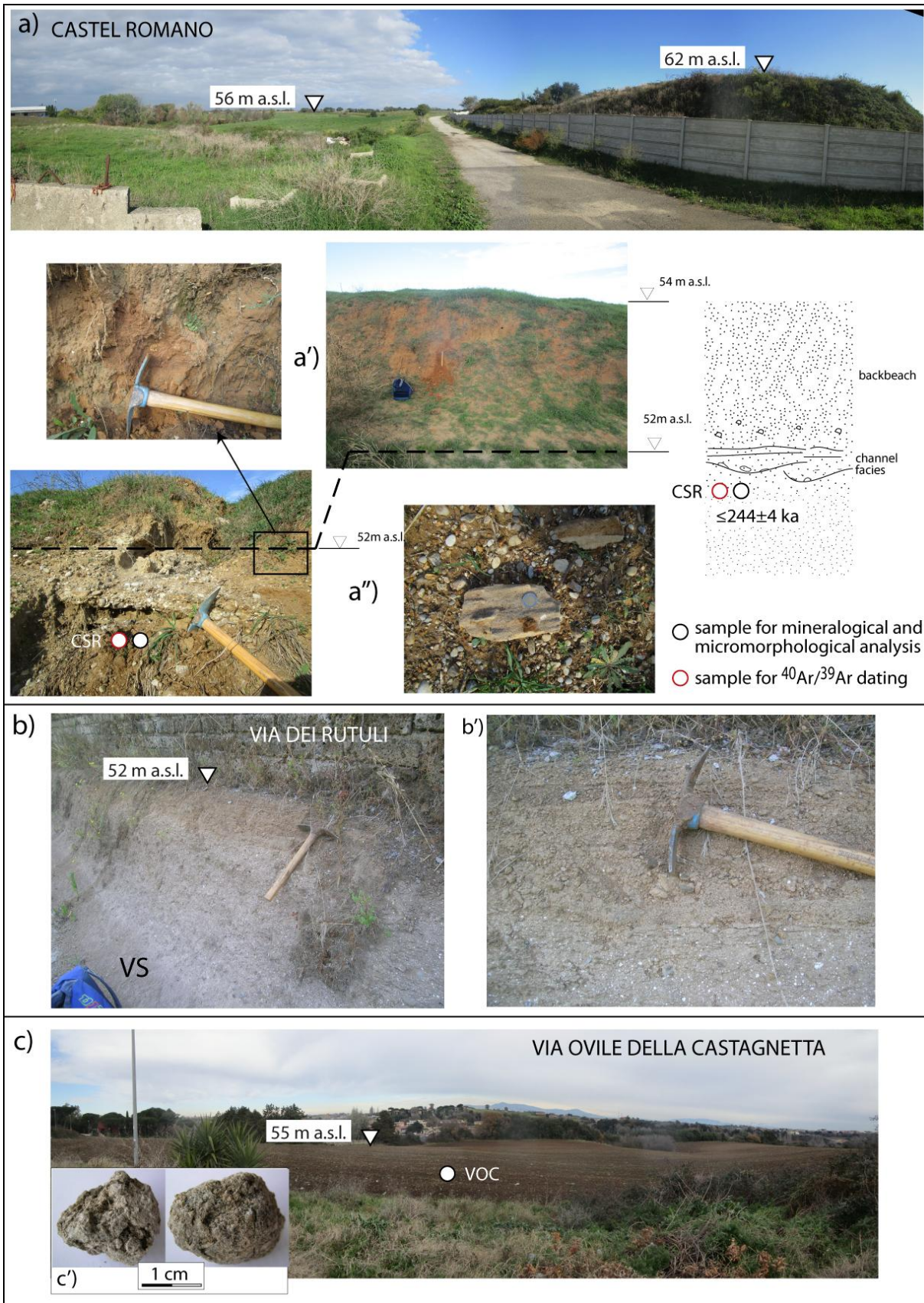
443 The 60-67 m paleo-surface has a wide expression to the north of the Tiber (Figure 2).
444 However, no sedimentary succession is apparently associated with this paleo-surface, its
445 geologic substrate consisting of different, older volcanic deposits, ranging 561-400 ka (e.g.,
446 Karner and Marra, 1998; Marra et al., 2016b), which form the hilltops in this area.
447 Consequently, the 60-67 paleo-surface in this area should be considered as a non-depositional
448 terrace, possibly generated by uplift-induced erosional processes in the near-shore sector,
449 similar to the higher level paleo-surface of 71-77 m in this sector.

450

451 **4.2.5 Paleo-surface 51-57 m a.s.l.**

452 This paleo-surface (red triangles in Figure 2 and 3) has a prominent expression in the Ponte
453 Galeria area north of the Tiber mouth, where solid geochronologic constraints correlate it
454 with MIS 7, as noted in Marra et al. (2016a). It is rather well preserved along the southeastern
455 side of the Tiber Valley, south of the river mouth, and in the southernmost sector between
456 Ardea and Anzio, while it disappears along the coastal reach facing the TML morpho-
457 structural height (Figure 3). However, two fragments of coastal terrace are preserved
458 immediately north of this sector, and one of these (Castel Romano -CSR) provides good
459 exposure of the terrains underlying the paleo-surface. At CSR a large level area at elevations
460 ranging 51-56 m a.s.l. is bordered to the west-northwest by a steep, 6 m high scarp (Figure
461 9a), separating it from the other wide level area of Podere Carafa, ranging 71-79 m a.s.l. (see
462 Figure 3).

463



464

465 Figure 9 - Photographs and stratigraphic schemes showing the 51-57m a.s.l. paleo-surface and
 466 the sections from which samples analyzed in the present study were collected. See text for
 467 comments.

468

469 The 60-67 m terrace is not preserved between the two paleo-surfaces in this area, which are
 470 connected by a gentle incline degrading from ca. 70 m to 62 m a.s.l., behind the sub-vertical
 471 scarp. The 51-56 m paleo-surface at CSR is dissected by a gully exposing on its banks a
 472 reddened, massive sand deposit, 2 m thick (Figure 9a'), overlying a ca. 50 cm thick layer with
 473 gravel lenses and sandstone horizons with ripple marks (Figure 9a"). This braided channel
 474 facies overlies a massive sand deposit in which sample CSR for mineralogical analysis and
 475 $^{40}\text{Ar}/^{39}\text{Ar}$ dating was collected.

476 A different geologic substrate represented by the PL characterizes the 51-57 m paleo-surface
 477 within the Ardea Basin. However, exposure at Via dei Rutuli (VR, see Figure 3) provides
 478 evidence of a conglomeratic layer above the PL at 52 m a.s.l. (Figure 9b), which testifies the
 479 occurrence of a transgressive deposit that should be considered the coastal deposit associated
 480 with the 51-57 terrace in this area. It is a bedded, fining upward, 50 cm thick sand and gravel
 481 layer, containing well-rounded scoria clasts from the underlying pyroclastic deposit, which is
 482 erosionally truncated at the top (Figure 9b'). Evidence from another site within the Ardea
 483 basin (Via Ovide della Castagnetta -VOC, Figure 3) suggests that a fine-grained, lagoon deposit
 484 forms the upper portion of the 51-57 terrace in this area. Here, a wide paleo-surface around
 485 55 m a.s.l. (Figure 9c) consists of a brown, mature paleosol in which one sample (VOC) was
 486 collected and analyzed for micromorphology. The occurrence of abundant, rounded
 487 calcareous concretions (Figure 9c'), which are uncommon in shallow soils developed directly
 488 upon the siliceous volcanic deposits, suggests the presence of a horizon of calcareous mud, as
 489 typically observed in the lagoon deposits of the MIS 7 Vitinia Formation (Karner and Marra,
 490 1998) associated with the 51-57 paleo-surface in the northern coastal sector.

491

492 4.3 Micromorphological analyses

493 Results of thin section observations are summarized in Table 1.

494

495

496

497

498

TS ¹	Microstructure	Lithology	Groundmass ²	c/f ratio	Rel Dist ³	Pedofeatures
TML-CC	-	Matrix: 15 -20% fine sands (quartz; rare feldspar; chert; metamorphic rock fragments) Inside nodules: well sorted fine sands ($\pm 45\%$) (quartz; feldspar;	Orange (PPL) clay with SS and GS fabric	20/80 (matrix) 50/50 (nodules)	OP (matr.) SSP (nod.)	Matrix: layered clay coatings and infillings, limpid and

		chert; metamorphic rock fragments; pyroxene)				silty clay, broad extinction lines, frequent.
CR1	Basic MS type: close porphyric	Fine sand (5%); Medium sand (60-65%) Lithology: quartz; feldspar; chert; pyroxene; metamorphic rock fragments; epidote. Sub-rounded and sub-angular grains.	Reddish (PPL) clays with SS and GS b-fabric	70/30	CP	Limpid clay coatings and infillings, 1st order yellow interference colors; broad extinction lines, occasional superimposed Fe coatings.
VDT	Subangular blocky, moderate	Very fine sand (5-10%); Fine sand (5%); Medium sand (5-10%) Lithology: quartz; chert; pyroxene (rare); Sub-rounded and sub-angular grains.	Orange (PPL) clay with CS and GS b-fabric	20/80	OP	Limpid clay coatings, strongly deformed, frequent. Disorthisic Fe/Mn nodules, typic and concentric, frequent, rounded.
VOC	Basic MS type: single-spaced porphyric	Very fine sand (\pm 5%); Fine sand (15-20%); Medium sand (25-30%) Lithology: quartz; feldspar; chert; pyroxene; amphibole; volcanic scoria (rare); metamorphic rock fragments. Sub-rounded and sub-angular grains.	Yellowish (PPL) clays with GS b-fabric	60/40	SSP	Limpid clay coatings, strongly deformed, frequent. Disorthisic Fe/Mn nodules, typic and concentric, frequent, rounded.

499

500 **Table 1 – Description of thin sections**

501 ¹ TS = Thin Section

502 ² B-fabric: SS = Stipple speckled; PS = poro striated; GS = grano striated; CS = cross striated

503 ³ Rel Dist = Related distribution pattern: CP = close porphyric; SSP = single-spaced porphyric; OP = open porphyric

504

505

506 **4.3.1 Concretionary layer from Tenuta Monte di Leva: sample TML-CC**

507 Micromorphological analysis of this sample collected from the TML concretionary layer

508 shows that the nodules are iron and manganese concretions that entrap sediments differing

509 from those in the surrounding groundmass. The main differences between the sediments

510 within the nodules and those in the matrix around them are as follows:

511 (a) The degree of sorting, which inside the nodules is good, with grains in the fine sand class,

512 indicating that the nodules formed in aeolian or alluvial sands (e.g., channel facies).

513 (b) The lithology: the matrix consists only of weathering resistant species, whereas in the

514 nodules some volcanic minerals (pyroxenes – Fig. S1) are preserved, and feldspar (e.g.,

515 microcline) is more abundant than in the surrounding matrix.

516 The matrix around the nodules shows the effects of marked pedogenesis. It is in fact very clay-

517 rich and in the coarse fraction only weathering resistant material is preserved (quartz, chert,

518 metamorphic rock fragments – predominantly quartzite). Clay coatings, pertaining to several
519 superimposed episodes of clay illuviation, are very strongly developed (Fig. S2). They occur as
520 superimposed limpid and silty clay coatings or as coatings deformed due to shrink-swell
521 phenomena.

522 Albeit that the nodules may be allochthonous (i.e., formed elsewhere and then transported and
523 re-deposited after being eroded), observations attest that they contain remains of the former
524 parent material on which pedogenesis has taken place, “preserving” it from successive
525 weathering. Weathering and pedogenesis subsequently affected the groundmass but were
526 impeded within the nodules.

527

528 **4.3.2 Sand deposit from Colle Rotondo: sample CR-1**

529 The sand fraction is composed of a mixture of siliciclastic and volcanoclastic (i.e. pyroxenes –
530 augite) mineral species. The moderate sorting, the grainsize centered on the medium sand
531 granulometric class, and the slight rounding of the grains are compatible with an aeolian
532 (backbeach) sediment. There are no traces of reworking due to surface runoff or similar water
533 and gravity-triggered slope processes. Pedogenesis is at an initial stage, especially compared
534 to other samples from this study. Incipient reorganization of the groundmass, giving rise to a
535 stipple-speckled b-fabric, is observed. Weak traces of incipient clay illuviation, such as thin
536 clay coatings around skeletal grains, also point to an initial/moderate level of pedogenesis
537 (Fig. S3). The weatherable minerals in the coarse fraction – especially pyroxenes – are
538 abundant and do not show traces of weathering.

539

540 **4.3.3 Paleosol from Via dei Tigli: sample VDT**

541 This sample shows the highest degree of pedogenic weathering amongst the analyzed
542 samples. The abundant clay in the groundmass shows orange-red colors resulting from the
543 strong oxidation, and the clay are the outcome of repeated cycles of clay illuviation. Strong
544 vertic processes (i.e.: internal turnover of soil material) led to the digestion of the illuvial
545 clays in the fine mass and to the formation of strongly developed cross-striated and grano-
546 striated b-fabric types (Fig. S4, S5). Also the nodules of iron and manganese owe their
547 morphology to the strong shrink-swell phenomena in the sample (which led to the formation
548 of concentric nodules with strong rounding). The coarse fraction is predominantly composed
549 of weathering-resistant species (quartz and chert), albeit minor amounts of pyroxenes and
550 unaltered volcanic glass are still present. The latter might derive from a ‘fresher’ or more
551 recent input of volcanoclastic material into the soil during its formation. The poor sorting, sub-

552 angular morphology and medium-fine sand grain size of the siliciclastic fraction do not match
553 the expected characteristics of an aeolian input, strongly suggesting an alluvial/colluvial
554 origin.

555

556 **4.3.4 Paleosol from Via Oville della Castagnetta: sample VOC**

557 The sorting of the coarse fraction is low. The sample has the highest percentage of volcanic
558 mineral grains (pyroxenes and amphiboles – see Fig. S6) in the studied set, included the loose
559 sand samples. The fine fraction derives from clay illuviation, which ultimately triggered vertic
560 processes and the digestion of clay coatings within the groundmass, the development of a
561 grano-striated b-fabric, and the formation of concentric iron and manganese nodules.
562 Grains are predominantly in the fine and medium sand fraction, and show subrounded and
563 rounded morphologies. The low sorting and the rounding of iron and manganese nodules
564 indicate reworking and redeposition of the material. The presence of rare calcite infillings
565 indicates re-carbonation of the profile due to the effect of a dissolved carbonate-rich
566 groundwater table (Fig. S6). Abundant, large (1-2 cm) carbonatic nodules also occur in the
567 deposit.

568

569 **4.4 Mineralogical analyses in thin section**

570 **4.4.1 sample TML-SA**

571 Due to the granulometric bias introduced by sieving, it is not possible to ascertain the
572 sedimentary environment in which the deposit formed through thin section observation.
573 Nevertheless, it can be said that TML-SA is characterized by scanty medium and coarse sand
574 fraction, and by fine material possibly indicating pedogenesis. Indeed, the fine material was
575 observed before the sieving and also after it, especially in the form of “pseudosands” which
576 survived the sieving procedure. The nature of the sand grains is essentially siliciclastic (Table
577 2), with a very minor volcanoclastic fraction and lack of volcanic scoriae. Grains have a
578 subangular morphology.

579

580

Minerals	TML - SA	PC-SA	CSRM-SA
	%	%	%
Quartz	64	66	35
Metamorphic rock fragments	20	19	35
Chert	12	10	16
Feldspar	3	2	5
Pyroxene	1	3	8
Amphibole	1	0	0
Volcanic scoria	0	0	1

Total siliciclastic %	98	97	91
Total volcanoclastic %	2	3	9
<i>Counted grains (n)</i>	152	156	154

581
582
583

Table 2: results of petrographic determination of sands

584 Quartz, chert, metamorphic rock fragments (mainly quartzite with minor amounts of schist)
585 and feldspar have been grouped under the “siliciclastic” category. Pyroxene (mostly augite
586 and monocline pyroxene, diallagio), amphiboles (green and brown hornblende) and volcanic
587 scoria belong to the “volcanoclastic” category.

588

589 **4.4.2 Sand deposit at Podere Carafa: sample PC-SA**

590 The sand displays strikingly similar grain composition (Table 1) and morphology as that of
591 sample TML-SA.

592

593 **4.4.3 Sand deposit at Castel Romano: sample CSR-SA**

594 This sand sample is characterized by medium grain size with a subrounded morphology and
595 no fine matrix. Mineralogical composition displays a higher percentage of volcanic species in
596 comparison with the other sand samples (Table 1).

597

598 **4.5 X-ray and SEM analysis**

599 Results of diffractometric analyses are summarized in the diagrams of Figure 10.

600 Calcic clinopyroxene is ubiquitous in the pyroclastic rocks of the Colli Albani volcanic district.

601 In addition, amorphous material derived from the weathering of volcanic glasses is typical of

602 soils developed on pyroclastic rocks (generally, this soil component is identified in the RDX

603 by the increase of counts in the region at lower 2Θ). Consequently, the height of

604 clinopyroxene peak at $2\Theta=29.85^\circ$, as well as that of amorphous material at $2\Theta=4^\circ$, with

605 respect to quartz peak at $2\Theta=26.65^\circ$ in the RDX can be assumed as an indicator of the

606 abundance of volcanic components forming the soil. This provides an index (i.e.

607 $Qtz/(AM+Cpx)$ in Table 3) to distinguish the soils developed above a primary volcanic

608 substrate (Index <6) from those overlying sedimentary deposits (Index >6).

609 Notably, quartz is present in all the soils developed above volcanic deposit and its abundance

610 generally increases with decreasing depth as evidenced by magnitude of the peak at

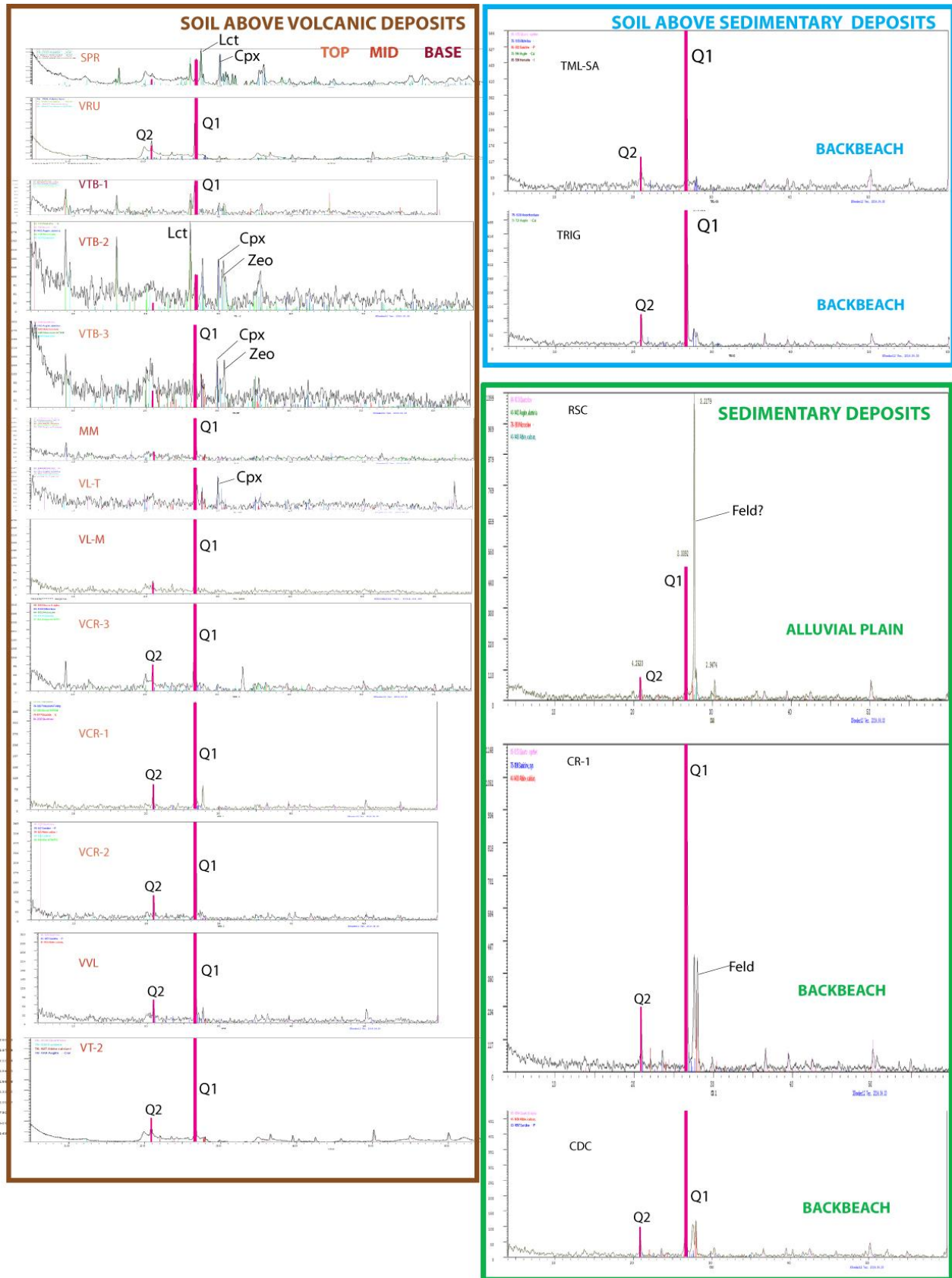
611 $2\Theta=26.65^\circ$ (Q1 Figure 10a). Quartz is practically absent closer to the base of the soil in VTB-1,

612 and is scarce in the middle of the soil in VTB-2 and in Monte Migliore (MM). However, it is also

613 abundant in the middle of VVL and VL, where the Q1 peak is comparable with that of all the

614 surface samples. A marked quartz peak is present in sample VdT-2, from the soil developed

615 above the Villa Senni deposit on the 61-67 terrace, for which the siliciclastic fraction has been
616 investigated in thin section for micromorphology on sample VdT-1. However, excluding the
617 sample VCR-1, notably the closest one to the inferred sedimentary/volcanic transition in
618 Figure 11, all the soils developed above volcanic deposit show higher amount of AM+Cpx
619 (>12) in comparison with the others soils analyzed in this study (Table 3).



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 621
 622
 623
 624

Figure 10 - Diffraction patterns of the soil and sediment samples. In inset a' diffraction patterns are...
 Vertical axes are normalized to the same scale; full-resolution original diagrams are provided
 in Suppl. Mat. #1B. See text for comments.

625 Moreover, quartz abundance decreases with the distance from the inferred paleo-shoreline in
 626 soils developed above the volcanic substrate. In order to verify this observation, we have
 627 collected two samples in the inland sector at the foot of the Colli Albani peri-caldera ring (SPR
 628 and RUT, Figure 11) and we have normalized results of diffractometric analyses performed
 629 with a different equipment (see Methods in Supplementary Material #2) by re-analyzing
 630 samples VTB-1 and VTB-3 with them (Table 3). As shown in Figure 10 and Table 3, Q1 peaks
 631 and AM+Cpx/Qz are the highest one for these samples.

632 Apart for the discriminating AM+Cpx/Qz ratio, diffractograms of soils above sedimentary
 633 deposits differ from those above volcanic deposits only for the slightly larger magnitude of the
 634 main quartz peak Q1, and for the presence of a second quartz peak close to 10 (Q2). These
 635 peaks are much higher in the sediment samples which also display a remarkable peak
 636 corresponding to the pyroxene. Finally, the smaller magnitude of the quartz and pyroxene
 637 peaks in the fine sediment sample CDC suggests that magnitudes are also proportional to
 638 grain size of the siliciclastic component.

639 Abundance, dimension and morphology of the Quartz and K-feldspar grains occurring in
 640 selected samples (VTB-1, TML-SA, VCR-1, CR1) have been analyzed at the SEM and discussed
 641 in section 5.1. Microphotographs are provided in Supplementary Material #2.

642

	SOILS ABOVE VOLCANIC DEPOSITS															SOILS ABOVE SEDIMENTARY DEPOSITS				
	VTB-1	VTB-2	VTB-1	VV	VL-M	VL-T	MM	VTB-1*	VTB-3*	VRU*	SPR*	VdT-2*	VCR-3	VCR-2	VCR-1	TRIG	TML-SA	RSC	CDC	CR-1
Amorphous	305	240	8000	58	54	121	45	68	9900	6100	8500	4750	80	70	30	52	59	55	45	110
Qtz	290	122	8000	320	270	147	150	0	20700	15977	6650	26343	316	349	394	520	586	1099	501	1168
Cpx	165	165	11500	0	10	118	15	40	9300	750	8000	550	25	0	10	20	20	40	20	0
TOT	760	527	27500	378	334	386	210	108	39900	22827	23150	31643	421	419	434	592	665	1194	566	1278
Amorphous	40	46	29	15	16	31	21	63	25	27	37	15	19	17	7	9	9	5	8	9
Qtz	38	23	29	85	81	38	71	0	52	70	29	83	75	83	91	88	88	92	89	91
Cpx	22	31	42	0	3	31	7	37	23	3	35	2	6	0	2	3	3	3	4	0
TOT	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Qtz/Cpx+AM	0,6	0,3	0,4	5,5	4,2	0,6	2,5	0,0	1,1	2,3	0,4	5,0	3,0	5,0	9,9	7,2	7,4	11,6	7,7	10,6
Cpx+AM	62	77	71	15	19	62	29	100	48	30	71	17	25	17	9	12	12	8	11	9

643

644 Table 3 - X-ray powder diffraction (XRPD) data. Summary of absolute abundances of
 645 mineral phases in the analyzed samples (*samples analyzed with a different
 646 equipment, see Methods in Supplementary Material #2).

647

CR3	
Age (ka)	$\pm 2\sigma$ (ka)
127,7	$\pm 11,3$
130,9	$\pm 11,2$
131,0	$\pm 9,6$
131,7	$\pm 9,7$
133,4	$\pm 13,7$
134,0	$\pm 14,3$
138,3	$\pm 6,3$
140,6	$\pm 12,5$
169,5	$\pm 6,9$
169,7	$\pm 11,7$
177,6	$\pm 8,3$
198,4	$\pm 7,3$
245,3	$\pm 6,6$
249,9	$\pm 7,2$
250,7	$\pm 6,5$
251,6	$\pm 6,6$
298,9	$\pm 5,6$
375,6	$\pm 4,9$
379,1	$\pm 5,6$
392,9	$\pm 9,6$
393,5	$\pm 4,8$
400,2	$\pm 4,6$
401,4	$\pm 5,1$
403,6	$\pm 4,7$
407,3	$\pm 5,6$
407,8	$\pm 4,6$
410,7	$\pm 6,5$
416,5	$\pm 3,5$
418,1	$\pm 4,6$
421,7	$\pm 3,8$
446,8	$\pm 4,6$
459,2	$\pm 5,1$
495,5	$\pm 6,5$
498,4	$\pm 4,8$
503,2	$\pm 4,1$
1289,3	$\pm 6,5$
1289,9	$\pm 3,9$
1293,0	$\pm 6,9$
1313,1	$\pm 3,5$
youngest population:	
134,2	$\pm 3,5$
249,3	$\pm 3,4$

648

654

655

656 Table 4 - $^{40}\text{Ar}/^{39}\text{Ar}$ ages of dated samples

657

658

649

TML-SA	
Age (ka)	$\pm 2\sigma$ (ka)
151,1	$\pm 27,6$
165,5	$\pm 28,5$
166,6	$\pm 27,9$
171,0	$\pm 24,9$
181,7	$\pm 25,4$
189,3	$\pm 54,3$
216,5	$\pm 6,0$
239,9	$\pm 4,7$
246,2	$\pm 17,8$
250,0	$\pm 6,6$
252,3	$\pm 7,1$
257,6	$\pm 5,1$
262,8	$\pm 22,7$
266,0	$\pm 20,0$
287,5	$\pm 72,5$
316,8	$\pm 18,7$
329,8	$\pm 20,8$
335,5	$\pm 96,7$
351,5	$\pm 15,7$
361,0	$\pm 40,6$
368,2	$\pm 32,7$
369,5	$\pm 20,0$
371,2	$\pm 21,5$
372,6	$\pm 18,7$
382,2	$\pm 23,2$
389,6	$\pm 23,0$
398,9	$\pm 16,2$
409,6	$\pm 5,9$
422,9	$\pm 63,3$
430,5	$\pm 10,9$
435,7	$\pm 8,7$
446,4	$\pm 5,6$
504,4	$\pm 5,6$
541,7	$\pm 5,0$
549,4	$\pm 5,4$
551,8	$\pm 4,3$
557,0	$\pm 40,2$
589,3	$\pm 4,4$
600,0	$\pm 6,4$
1328,9	$\pm 8,0$
1339,3	$\pm 15,9$
youngest population:	
169	± 11

650

651

CSR-SA	
Age (ka)	$\pm 2\sigma$ (ka)
232,3	$\pm 19,8$
240,9	$\pm 8,2$
244,5	$\pm 5,7$
246,8	$\pm 6,9$
263,1	$\pm 4,6$
263,7	$\pm 29,1$
310,1	$\pm 16,3$
395,5	$\pm 5,0$
407,9	$\pm 4,4$
476,6	$\pm 7,1$
488,3	$\pm 5,3$
494,5	$\pm 4,7$
500,8	$\pm 6,8$
508,5	$\pm 3,5$
542,1	$\pm 17,2$
552,1	$\pm 9,0$
563,1	$\pm 6,2$
597,3	$\pm 3,7$
625,7	$\pm 6,7$
805,2	$\pm 9,7$
youngest population:	
244,0	$\pm 3,8$

652

CAR-SA	
Age (ka)	$\pm 1\sigma$ (ka)
298,19	$\pm 3,50$
397,35	$\pm 2,69$
397,55	$\pm 2,50$
401,16	$\pm 3,23$
401,50	$\pm 6,70$
401,92	$\pm 4,30$
409,08	$\pm 4,09$
409,45	$\pm 2,28$
410,43	$\pm 3,01$
416,80	$\pm 2,14$
417,80	$\pm 1,90$
417,86	$\pm 27,38$
420,18	$\pm 3,26$
430,43	$\pm 2,92$
447,50	$\pm 15,16$
461,11	$\pm 3,89$
468,78	$\pm 18,49$
523,49	$\pm 3,21$
566,40	$\pm 2,82$
580,99	$\pm 3,19$

653

659 **4.6 $^{40}\text{Ar}/^{39}\text{Ar}$ data**

660 Single crystal age data for the three analyzed samples are reported in Table 4. Full analytical
661 data are provided in Supplementary Material #3.

662 **4.6.1 Sample CR3**

663 Thirty-nine sanidine crystals extracted from the sand sample collected ca. 90 cm below the
664 ground surface in Colle Rotondo provided a wide age spectrum, ranging 1.31 through 0.13 Ma. A
665 youngest population of eight crystals yielded a weighted mean age of 134 ± 3.5 ka.

666 **4.6.2 Sample TML-SA**

667 Forty-one sanidine crystals extracted from the sand sample collected ca. 60 cm below the
668 ground surface in Tenuta Monte di Leva provided ages ranging 1.34 through 0.15 Ma. A
669 youngest population of six crystals yielded a weighted mean age of 169 ± 11 ka.

670 **4.6.3 Sample CSR-SA**

671 Twenty sanidine crystals extracted from the sample collected in the fluvial sand cropping out
672 in Castel Romano provided ages ranging 0.80 through 0.23 Ma. A youngest population of four
673 crystals yielded a weighted mean age of 244 ± 4 ka.

674 **4.6.4 Sample RSC-SA**

675 Twenty sanidine crystals extracted from the sample collected in the fluvial sand cropping out
676 in Riserva Carpineto provided one isolated, youngest crystal of 298 ± 3.5 ka. The majority of
677 the crystal ages are spread in the interval 398-468 ka, with three oldest crystals ranging 523 -
678 581 ka.

679

680 **5. Discussion**

681 **5.1 Soils and paleo-surfaces**

682 Analysis of soil samples for the present study has been conducted aimed at identifying their
683 sedimentologic and petrographic features, in order to understand their origin and the
684 paleogeographic conditions in which they formed. Pedologic considerations and a complete
685 study of the processes involved the formation of these soils, as well as laboratory
686 granulometric analyses are beyond the scope of the present work. Our main scope is to verify
687 to what extent the present ground surfaces characterized by the same elevations range
688 represented in Figure 2 and 3 can be considered indicative of the original paleo-surfaces
689 representing the ancient coastal settings. In particular, we want to quantify the possible
690 amount of later deposition, or erosion, which may have increased or decreased, respectively,
691 the average elevation of these paleo-surfaces, therefore affecting our estimation of the sea-
692 level related with the corresponding coastal terrace.

693 When studying the composition of the soils developed above the reconstructed paleo-
694 surfaces, some preliminary considerations are necessary. In particular, when the paleo-
695 surfaces of highest order are considered (i.e. those ranging 98-108, 80-89, and 71-79 m a.s.l.,
696 Figure 3), we must realize that the sub-horizontal attitude of these isolated, plateau-like
697 sectors precludes alluvial sedimentation, almost completely. Furthermore, the whole
698 catchment area drained by these paleo-surfaces is developed above volcanic deposits.
699 Therefore, the siliciclastic component of the soils above the paleo-surfaces of this sector,
700 which in the X-ray diagrams is sometimes predominant, can only have the following two
701 origins:

- 702 i. it can be a back-beach to coastal plain sediment originally deposited above the volcanic
703 substrate when the paleogeographic conditions allowed (i.e.: before the regional uplift, when
704 the paleo-surface represented a coastal environmental setting) (BB and AL in Figure 11a);
- 705 ii. it can be an aeolian sediment (i.e., loess-like) accumulated above the volcanic deposits
706 through air-fall emplacement and successively diffused within the soil by vertic processes
707 (i.e.: internal turnover of soil material originated by pedogenetic processes).

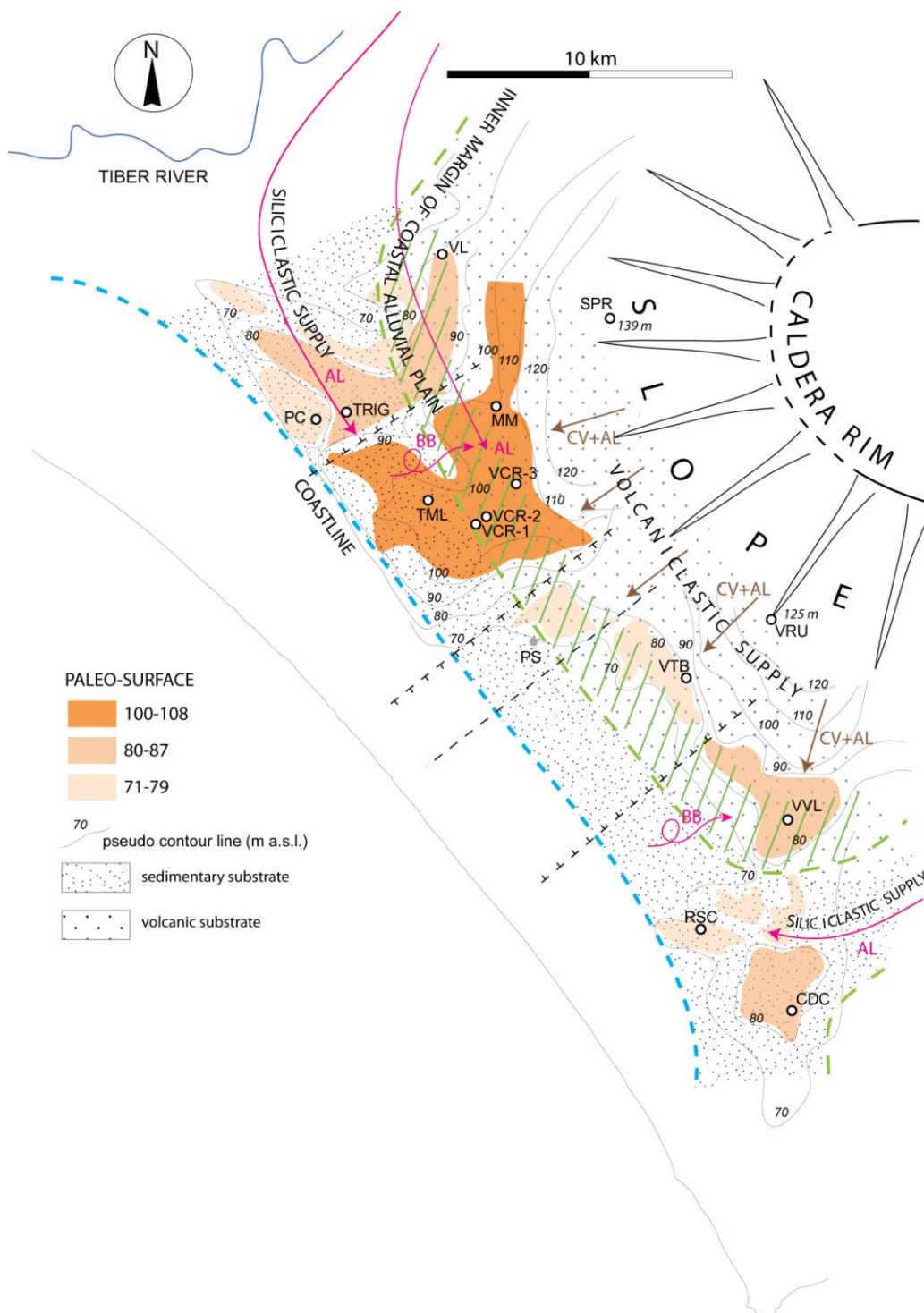
708 Recognizing the origin of this siliciclastic sediment is therefore fundamental in order to
709 reconstruct the paleogeographic setting of these paleo-surfaces, correctly, as shown in Figure
710 11, in which the paleogeographic scenario is illustrated. The dashed green line in Figure 11
711 separates the sampling sites where field observation have shown that the present soil overlies
712 sedimentary sand deposits (to the southwest), from those where the soil is developed above
713 the volcanic deposit of Pozzolanelle (to the northeast), as reported also in the cross-section of
714 Figure 12. The oblique green lines indicate the area where the siliciclastic fraction in the
715 analyzed soils is predominant.

716 Composition of the analyzed soils overlying the volcanic deposit of Pozzolanelle, with
717 abundant quartz and feldspar, combined with micromorphological and SEM analyses which
718 confirm the sedimentary origin of the quartz grains but rule out an aeolian (loess-like) origin,
719 at least for the larger fraction ($>200\ \mu\text{m}$; Figure S7), demonstrate that these soils affect thin (\leq
720 1 m) layers of alluvial and backbeach, predominantly siliciclastic deposits. In keeping with
721 this interpretation, quartz abundance strongly decreases in soil samples collected in more
722 inland locations (SPR, RUT), far from the inferred paleo-coastline (Figure 10).

723

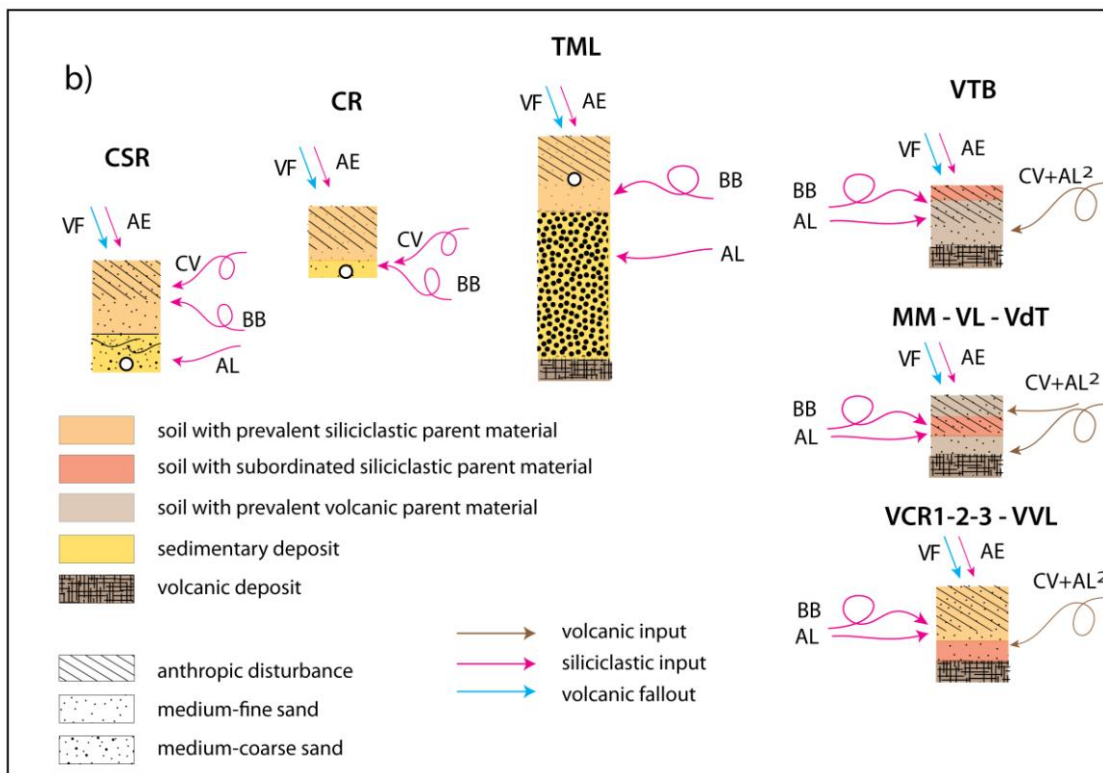
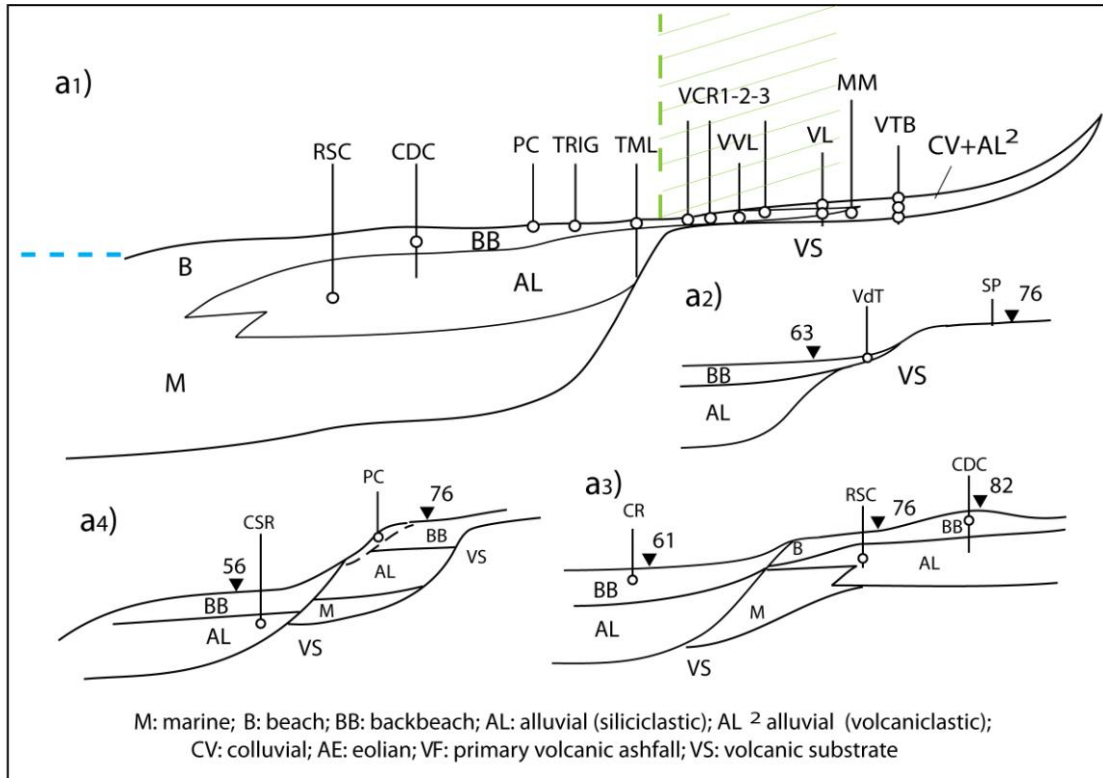
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726

727 Figure 11- Paleogeographic reconstruction of the MIS 9 coastal setting. Stratigraphic
 728 investigations and sedimentologic, micromorphologic, mineralogic and petrographic analyses
 729 on sediment and soil samples have allowed to detect a transitional zone (oblique green
 730 dashes) corresponding with the inner margin of the coastal plain, where a thin horizon of
 731 backbeach to alluvial deposits overlaps the volcanic substrate. (see also cross-section in
 732 Figure 12a). This reconstruction evidences the occurrence of an original, homogeneous paleo-
 733 surface, subsequently disrupted and dislocated by tectonic movements, which gave rise to
 734 three main flat sectors at elevations ranging 100-108, 80-87, and 71-79 m a.s.l. (see text for
 735 comments).



736

737 Figure 12 - a1-4) Cross-sections restored from tectonic dislocation showing the original
 738 paleogeographic and sedimentary settings reconstructed in the area where the soil and
 739 sediment samples were collected. b) Origin of the different sedimentary inputs contributing to
 740 the formation of the deposits and the related soils at the top of the paleo-surfaces
 741 reconstructed in the present study. See text for comments.
 742

743 Alluvial/colluvial volcanic material (CV+AL in Figure 112b and 12), derived from the rocks
744 cropping out at the inner margin of the coastal alluvial plain (green dashed area in Figure 11),
745 were also continuously mixing with the alluvial and backbeach, predominantly siliciclastic
746 deposits transported by the Tiber River and deposited in the coastal plain. Moreover, air-fall
747 material including either loess-like sediment (AE in Figure 12b), or as primary air-fall
748 volcanic ash (VF in Figure 12b), also progressively accumulated above this soils and was
749 diffused by vertic processes into the sub-surface horizon. To this aeolian fraction must be
750 ascribed part of the K-feldspar observed in this section and evidenced in the diffractograms,
751 as well as part of the finest siliciclastic component.

752 Such an air-fall contribution must be extended to the soils developed above the sedimentary
753 deposits, in which the volcanic component is also represented by re-deposited mineral
754 species of the underlying sedimentary substrate, incorporated in the soil through colluviation,
755 surface water and wind transport (CV in Figure 12b).

756 These mechanisms are envisaged in Figure 12, showing the different paleogeographic and
757 sedimentary settings reconstructed in the area where the soil and sediment samples were
758 collected. The age spectra provided by sanidine crystals extracted from the lowest portion
759 (unaffected by agricultural disturbance) of the backbeach deposits above which the soils of
760 the 98-108 and of the 61-67 paleo-surfaces have developed (TML-SA, CR3; Figure 13),
761 compared to that of the "sealed" sedimentary deposit of the fluvial facies (RSC-SA, CSR-SA),
762 provide further insights to the processes described above.

763

764 **5.2 Age of the paleo-surfaces**

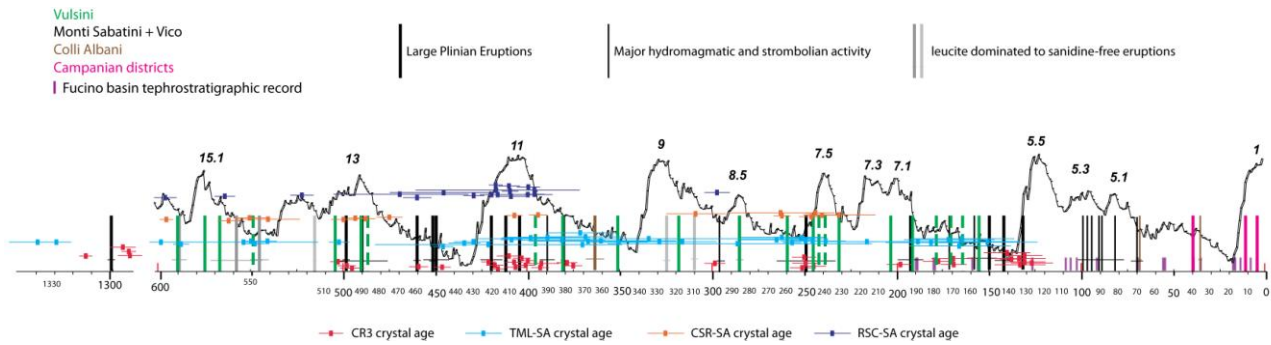
765 Youngest crystal ages of 232 ± 20 and 298 ± 4 ka yielded by sedimentary samples collected in
766 the alluvial facies (coastal plain) of the 51-57 m and of 71-79 m paleo-surfaces (CSR-SA and
767 RSC-SA) support correlation with MIS 7 and MIS 9 for the corresponding coastal terraces, as
768 discussed in the following sections.

769 Similarly, crystal ages of the samples collected from the backbeach facies at the top of the 98-
770 108 m and 61-67 m paleo-surfaces provide time constraints on the sedimentary processes
771 that acted in the time span following retreat of the coastline leading to progressive
772 impoverishment of sediment supply.

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Figure 13 - Crystal age spectra for the four sedimentary samples dated in the present study. Each cross represents the age of one dated sanidine crystal with the associated analytical error at 2σ . Comparison with the major eruptions occurred at the districts of the Roman Comagmatic province is provided. Each bar represents one eruption age (see Suppl. Mat. for details and references). Comparison with the oxygen isotope curve (Lisiecki and Raymo, 2005) is also shown. See text for comments.

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These age constraints are obtained by comparing the sample crystal ages with the eruptive histories of the volcanoes of the Latium Region, as provided in Figure 13. In considering the eruptive histories of the volcanic districts of Central Italy to compare age spectra yielded by the analyzed sedimentary samples reported in Figure 13, some preliminary considerations should be made.

i- These volcanoes are part of the "Roman Magmatic Province" (Conticelli and Peccerillo, 1992), characterized by a K-rich geochemistry which accounts for the diffuse presence of sanidine (KAlSi_3O_8) and leucite ($\text{K}[\text{AlSi}_2\text{O}_6]$) crystals, which also constitute the means of $^{40}\text{Ar}/^{39}\text{Ar}$ dating. However, while sanidine is a very resistant mineral species, leucite is highly sensible to weathering and easily alters to analcime (NaAlSi_2O): a process implying loose of K and compromising $^{40}\text{Ar}/^{39}\text{Ar}$ dating. Indeed, fluvially transported and beach deposits of several hundred kyr lack pristine leucite crystals. Therefore, in Figure 13 we have not reported all the sanidine-free eruption units (i.e., most of those of the Colli Albani volcanic district, see Gaeta et al., 2016 and references therein), while we have indicated those dominated by leucite (for which a lesser statistical occurrence is expected).

ii- When incorporation of crystals derived from primary fallout deposits is considered, the overall eastward regional winds and a consequent dispersal axis should be considered, along with the distance from the source area. Therefore, the major source of fallout deposits are the MSVD and Vico, while deposits from the Colli Albani and the Campanian districts have a low probability of representation in the stratigraphic record. One exception is represented by the sanidine-bearing activity of the Albano Center spanning 70 through 36 ka (Giaccio et al., 2009, and ref.), for which the small vent distance should have led to a well-represented crystal population, as also evidenced by outcrops in the southeastern area of the CAVD (e.g., Cisterna

807 di Latina, Latina Plain; Gatta et al., 2018, Sevink et al., 2018). Moreover, huge explosive
808 eruptions like the Campanian Ignimbrite (39 ka), Neapolitan Yellow Tuff (12 ka) and Avellino
809 pumice (4 ka) have provided widespread tephrostratigraphic markers in Latium (e.g., Giaccio
810 et al., 2017).

811 iii- The youngest eruptions should be better represented given the larger outcrop areas of the
812 products in comparison with the older ones, which are buried under more recent cover. This
813 reinforces the principle that a lack of crystals younger than the youngest population is
814 evidence of deposition prior to the immediately following eruption.

815 Consistent with the considerations above, Figure 13 shows that the age spectra of sanidine
816 crystals extracted from the four sand samples record a long eruptive history, ranging 0.60 -
817 0.13 Ma, plus one isolated cluster around 1.3 M. All crystal ages ≤ 0.6 Ma match known
818 eruptions of the Monti Sabatini, Vico and Vulcini volcanoes (Palladino et al., 2010; Sottili et al.,
819 2010; Marra et al., 2014, and ref. therein), while the oldest age matches that of early activity of
820 the Cimino volcanic complex (Everdin and Curtis, 1965, Nicoletti, 1969), located in the upper
821 Tiber Valley east of Vico. In contrast, all the eruption ages known from the literature that are
822 missing in the dated crystal populations, besides the sanidine-free Colli Albani products, also
823 correspond to sanidine-free or leucite-dominated products from Vico and Monti Sabatini
824 volcanic districts (Cioni et al., 1987; Sottili et al., 2004; Perini et al., 2004; Masotta et al., 2010;
825 Marra et al., 2014).

826 Based on these premises, in the following we discuss sample age implications on assessing
827 the age of the related paleo-surfaces.

828

829 **5.2.1 CSR-SA - 51-57 m paleo-surface**

830 Based on the sedimentary features of the underlying deposits and the top elevation ranging
831 51-57 m a.s.l. (Figure 9a-a"), the Castel Romano paleo-surface is interpreted as a backbeach
832 context, including the dune system superimposing the delta plain, developed during
833 highstand of MIS 7.3/7.1. Loose sanidine crystals occurring in the sand deposit of the braided
834 fluvial channel facies (Figure 9a'-a") yielded a youngest age of 232.3 ± 19.8 ka, part of a
835 statistically significant youngest population of 244.0 ± 3.8 ka (Table 4). Such datum has to be
836 considered a terminus post-quem which implies an age \leq MIS 7.5 (Figure 13), excluding and
837 age within MIS 9 and supporting correlation with highstand of the MIS 7.3/7.1.

838

839 **5.2.2 RSC-SA - 71-79 m paleo-surface**

840 The age spectrum of sample RSC-SA, collected within the alluvial plain deposit underlying the
841 71-79 paleo-surface at Riserva Carpineto, spans 581 - 398 ka, with a youngest crystal of
842 298 ± 3.5 ka (Table 4). Most crystal ages are clustered between 460 and 390 ka, coincident
843 with the large explosive phases emplacing sanidine-bearing products at Vico and Sabatini in
844 this time span (Figure 13). In contrast, no crystal deriving from the Villa Senni eruption unit
845 occurs in the dated sample, despite the sampled deposit overlies the Pozzolanelle eruption
846 unit of 365 ± 4 ka, consistent with the lack of sanidine phenocrystals in the Colli Albani
847 products. The age of one single crystal yielding 298 ± 3.5 ka has a poor statistical weight, and
848 should be regarded as broadly indicative of the lack of crystals younger than 300 ka. However,
849 it supports correlation with MIS 9 for the 71-79 m paleo-surface of Riserva Carpineto,
850 suggesting that sedimentation in the alluvial plain was sealed in the late stages of the MIS 9
851 highstand, excluding an age within MIS 7, while an age within MIS 11 is also excluded by the
852 fact that the sand deposit of Riserva Carpineto overlies the 365 ± 5 ka Pozzolanelle pyroclastic-
853 flow deposit.

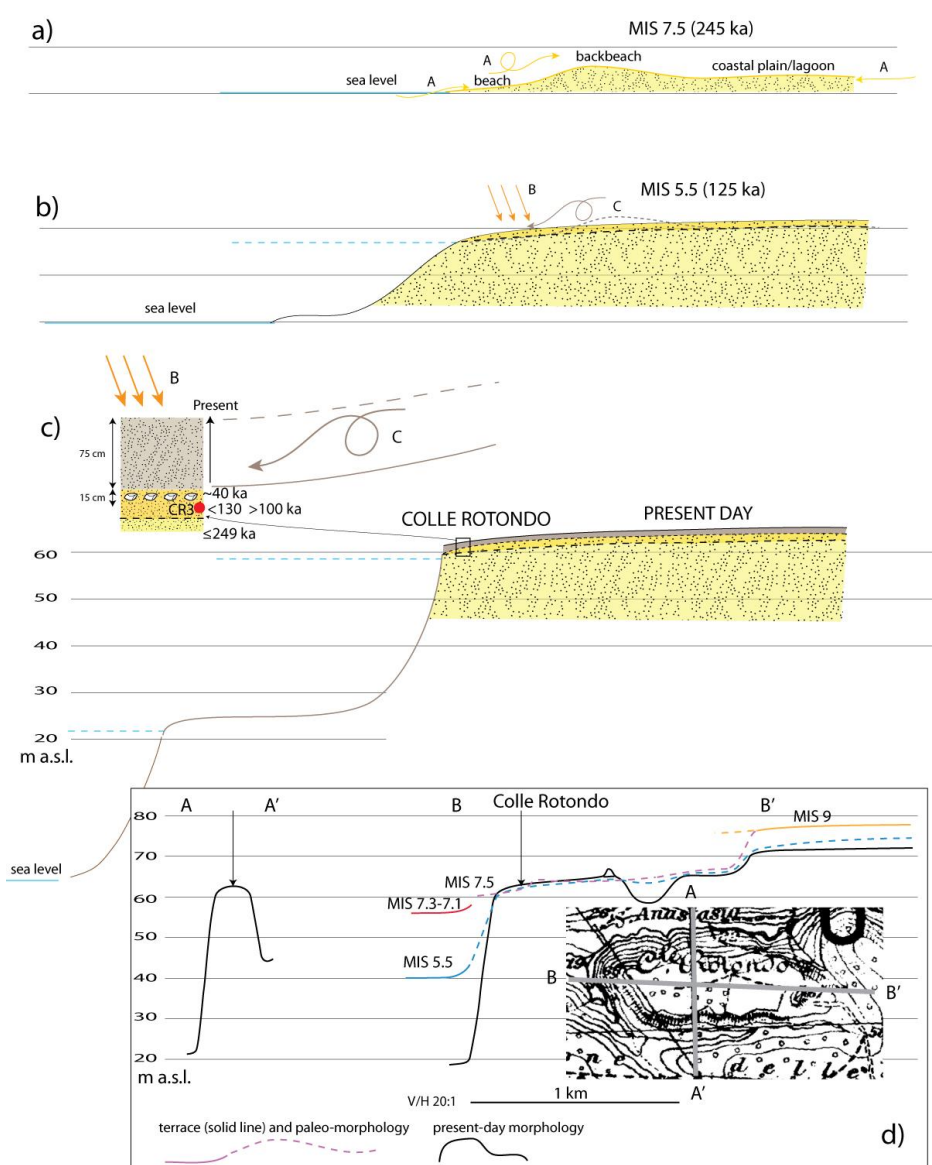
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855 **5.2.3 CR3 - 61-67 m paleo-surface**

856 Based on its sedimentologic features and the elevation ranging 61-67 m a.s.l., the Colle
857 Rotondo paleo-surface is interpreted as a backbeach context, either part of a dune system or
858 of a coastal alluvial plain, developed during highstand of MIS 7.5 (Figure 14a).

859 When the crystal ages from CR3 (red crosses in Figure 13) are compared to the eruptive
860 histories of the volcanoes of the Latium Region, it is apparent that no eruption younger than
861 134 ± 3.5 ka is recorded by the Colle Rotondo sand deposit. Indeed, given the large number of
862 dated crystals (39) and the wide age spectrum observed, the lack of any crystal from the
863 eruptive activity since 99 ka (see Figure 13) strongly suggests that the sample age should be
864 constrained between 132 and 99 ka. In particular, a large hydromagmatic phase occurred in
865 several volcanic centers of the MSVD, including Baccano, Stracciacappe, Le Cese, Acquarello,
866 Piana dei Falliti and Martignano, 132 ± 2 through 70 ± 3 ka (Sottili et al., 2010; Marra et al.,
867 2019b). While the earliest eruption that occurred at Baccano at 132 ± 2 ka is evidently
868 recorded by sample CR3, the lack of crystals from any later eruption strongly suggests a
869 terminus ante-quem of ca. 99 ± 3 ka (age of the products of the 2nd Baccano unit, erupted at
870 the beginning of the multi-vented hydromagmatic activity that continued until 70 ± 3 ka).
871 Although this age boundary to the deposit is in conflict with the attribution to the Uluzzian for
872 the lithic industry recovered at Colle Rotondo (Villa et al., 2018), we note that sample CR3 was
873 not collected in the stratum in conjunction with the artifacts, but in a side excavation.

874 Therefore, its correspondence with the archaeological layer is not safely established and
 875 provenance may be from the immediately underlying older substrate. In this latter case, the
 876 occurrence of the Uluzzian lithic assemblage at ca. 80 cm depth suggests that the overlying
 877 package of sediment accumulated during the last 40 ky. Such an accelerated accumulation
 878 may be linked with recent anthropic activity (e.g., agriculture), triggering soil mobilization. In
 879 contrast, the apparent age of ~134 ka for the sand layer at 80 cm depth does not conflict with
 880 an inferred age of 250-200 ka within MIS 7 for the Colle Rotondo paleo-surface, as discussed
 881 hereby based on a detailed analysis of the $^{40}\text{Ar}/^{39}\text{Ar}$ dating results.



882
 883 Figure 14 - Geomorphological and paleogeographic evolution of the Colle Rotondo plateau
 884 (see text for step by step comment and explanation).
 885

886 Like in the case of the sedimentary deposit sampled at Castel Romano which yielded a
 887 youngest crystal age of 232 ± 20 ka, consistent with a deposition age corresponding to the
 888 highstand of MIS 7.3-7.1 (i.e. 220-200 ka), an age ≥ 245 ka is expected for the fluvial/beach

889 sedimentary deposit at Colle Rotondo (supply A in Figure 14a) incorporating crystals derived
890 from erosion and re-deposition of the volcanic rocks erupted before that time, corresponding
891 to highstand of MIS 7.5 (i.e., 245 ka, see Figure 13). However, a progressively younger age is
892 expected for the backbeach deposit deriving from mixing of wind-blown sediment previously
893 deposited (supply C in Figure 14b) with crystals deriving from primary eruptions occurring in
894 the following time span (supply B in Figure 14b). Sample CR3 from Colle Rotondo yielded a
895 statistically significant (8 crystals) youngest crystal population of 134.2 ± 3.5 ka which is
896 characterized by significantly larger associated errors in comparison with the older
897 populations (see Table 5). In particular, these crystals yielded an average associated error of
898 ± 11 ka (corresponding to 8.2% when an age of 134 ka is considered) in comparison with an
899 average associated error of ± 5.4 ka for the 23 crystals yielding ages spanning 249.9 - 503.2 ka
900 (corresponding to 2.2% - 1.1%). These larger errors are due to the systematically smaller
901 dimensions of these crystals, evidencing their different means of transport in comparison
902 with that affecting the oldest ones, i.e.: wind vs. water. When this distinction is taken into
903 account, we find a second significant population age of 249.3 ± 3.4 ka, along with a few crystal
904 ages ranging 200-170 ka (Table 4 and Figure 13), consistent with an age within MIS 7.5 for
905 the original beach/alluvial deposit. An age $\geq 134 \pm 3.5 \leq 198.4 \pm 7.3$ ka is established for the
906 sampled backbeach deposit, showing that it accumulated above the MIS 7.5 paleosurface
907 during ca. 110 ky (i.e., 245 through 134 ka). The lack of crystals deriving from the eruptions
908 between 132 and 70 ka at the MSVD (see Figure 13), strongly suggests that the sampled layer
909 cannot be younger. Indeed, accidental absence of crystal ages within this time span is
910 statistically unlikely, given the eastern dispersal axis of the MSVD eruption (e.g. Sottili et al.,
911 2004; Di Rita and Sottili, 2019) and the occurrence of large explosive eruptions 90 through 70
912 ka at a number of centers of the so-called "Hydromagmatic Phase" (De Rita et al., 1983; Sottili
913 et al., 2010; Marra et al., 2019b). This fact also testifies that the depositional context
914 progressively changed after 245 ka, consistent with continued uplift of the coast and isolation
915 of the Colle Rotondo remnant paleo-surface, which was unaffected by deposition of water
916 transported sediment, like that occurring in alluvial plain or beach contexts, while only eolian
917 fallout deposits were emplaced, from then on. Since sample CR-1 occurs 90 cm below the
918 present ground level (Figure 14c), we can infer that present elevation of 63 m is a close
919 approximation of the MIS 7.5 paleo-surface, which is overlain by a thin eolian deposit
920 accumulated since 245 ka (input B in Figure 14c). Indeed, it is likely that samples collected
921 closer to the surface would yield progressively younger ages, consistent with incorporation of
922 crystals deriving from the younger eruptions of 100 ka and 90 through 70 ka. However, the

923 strong anthropic disturbance of the upper 70 cm of sediment prevents any reliable analysis.

924 Sample TML-SA from Tenuta Monte di Leva section provides further inferences on the

925 formation process of this thin eolian cover of the paleo-surfaces.

926

927

928

CR3	
Age (ka)	$\pm 2\sigma$ (ka)
134,0	$\pm 14,3$
133,4	$\pm 13,7$
140,6	$\pm 12,5$
169,7	$\pm 11,7$
127,7	$\pm 11,3$
130,9	$\pm 11,2$
131,7	$\pm 9,7$
131,0	$\pm 9,6$
392,9	$\pm 9,6$
177,6	$\pm 8,3$
198,4	$\pm 7,3$
249,9	$\pm 7,2$
169,5	$\pm 6,9$
1293,0	$\pm 6,9$
245,3	$\pm 6,6$
251,6	$\pm 6,6$
250,7	$\pm 6,5$
410,7	$\pm 6,5$
495,5	$\pm 6,5$
1289,3	$\pm 6,5$
138,3	$\pm 6,3$
298,9	$\pm 5,6$
379,1	$\pm 5,6$
407,3	$\pm 5,6$
401,4	$\pm 5,1$
459,2	$\pm 5,1$
375,6	$\pm 4,9$
393,5	$\pm 4,8$
498,4	$\pm 4,8$
403,6	$\pm 4,7$
400,2	$\pm 4,6$
407,8	$\pm 4,6$
418,1	$\pm 4,6$
446,8	$\pm 4,6$
503,2	$\pm 4,1$
1289,9	$\pm 3,9$
421,7	$\pm 3,8$
416,5	$\pm 3,5$
1313,1	$\pm 3,5$
youngest population:	
134,2	$\pm 3,5$

929

930

TML-SA	
Age (ka)	$\pm 2\sigma$ (ka)
335,5	$\pm 96,7$
287,5	$\pm 72,5$
422,9	$\pm 63,3$
189,3	$\pm 54,3$
361,0	$\pm 40,6$
557,0	$\pm 40,2$
368,2	$\pm 32,7$
165,5	$\pm 28,5$
166,6	$\pm 27,9$
151,1	$\pm 27,6$
181,7	$\pm 25,4$
171,0	$\pm 24,9$
382,2	$\pm 23,2$
389,6	$\pm 23,0$
262,8	$\pm 22,7$
371,2	$\pm 21,5$
329,8	$\pm 20,8$
266,0	$\pm 20,0$
369,5	$\pm 20,0$
316,8	$\pm 18,7$
372,6	$\pm 18,7$
246,2	$\pm 17,8$
398,9	$\pm 16,2$
1339,3	$\pm 15,9$
351,5	$\pm 15,7$
430,5	$\pm 10,9$
435,7	$\pm 8,7$
1328,9	$\pm 8,0$
252,3	$\pm 7,1$
250,0	$\pm 6,6$
600,0	$\pm 6,4$
216,5	$\pm 6,0$
409,6	$\pm 5,9$
446,4	$\pm 5,6$
504,4	$\pm 5,6$
549,4	$\pm 5,4$
257,6	$\pm 5,1$
541,7	$\pm 5,0$
239,9	$\pm 4,7$
589,3	$\pm 4,4$
551,8	$\pm 4,3$
youngest population:	
169	± 11

931

932

933

934

935

936 Table 5

937

938

939

940

CSR-SA	
Age (ka)	$\pm 2\sigma$ (ka)
263,7	$\pm 29,1$
232,3	$\pm 19,8$
542,1	$\pm 17,2$
310,1	$\pm 16,3$
805,2	$\pm 9,7$
552,1	$\pm 9,0$
240,9	$\pm 8,2$
476,6	$\pm 7,1$
246,8	$\pm 6,9$
500,8	$\pm 6,8$
625,7	$\pm 6,7$
563,1	$\pm 6,2$
244,5	$\pm 5,7$
488,3	$\pm 5,3$
395,5	$\pm 5,0$
494,5	$\pm 4,7$
263,1	$\pm 4,6$
407,9	$\pm 4,4$
597,3	$\pm 3,7$
508,5	$\pm 3,5$
youngest population:	
244	± 4

941

942

943 **5.2.4 TML-SA - 98-108 paleo-surface**

944 Much caution should be used in interpreting results for the TML-SA sample because it was
945 collected ca. 60 cm below the ground level within the soil horizon, in which both vertic
946 processes and anthropic disturbance might have caused incorporation of younger crystals
947 from the uppermost portion of the stratum.

948 However, the age spectrum of sample TML-SA, collected on the 98-108 paleosurface, is similar
949 to that of CR3 but yields a youngest minimum age of 169 ± 11 ka (Figure 13), evidencing a
950 relative older age, with respect to the sample collected on the 61-67 paleosurface of Colle
951 Rotondo.

952 These data suggest that the sampled sand deposit represents a sedimentary horizon that was
953 sealed from air-fall input by 170 ka, supporting the notion that the uppermost portion of the
954 reconstructed paleo-surfaces represents an accretionary horizon, built up mainly through
955 accumulation of alluvially/colluvially transported and, subordinately, air-fallen material.
956 Remarkably, also in this sample the youngest crystal population is characterized by larger
957 associated errors (Table 5), supporting the different mean of transport for this sedimentary
958 fraction which accumulated later, as an air-fall deposit above the underlying deposits of the
959 alluvial plain.

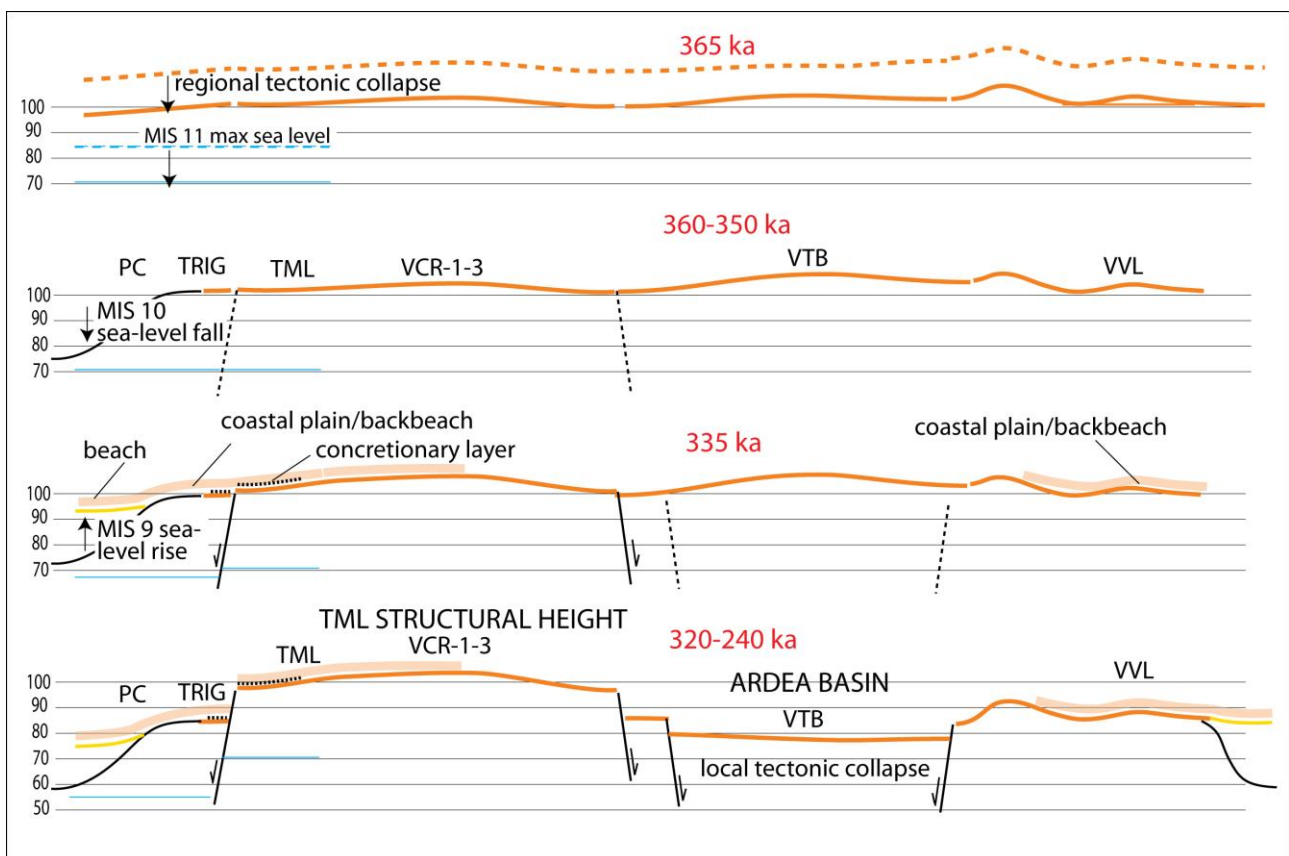
960 The very low sedimentation rate and the limited thickness of these accretionary horizons
961 overlying the "pristine" deposits forming the paleosurfaces, whose absolute age has been
962 determined by $^{40}\text{Ar}/^{39}\text{Ar}$ dating on "in stratum" samples from Castel Romano and Riserva
963 Carpineto, is consistent with the geomorphologic features of the TML and CR sectors,
964 precluding significant alluvial/colluvial sedimentation.

965

966 **5.3 The MIS 9 paleo-surface**

967 Geomorphological, lithostratigraphic, paleo-environmental and geochronological constraints
968 obtained for the deposits of the 71-79 m paleo-surface, and part of the 80-89 m and 98-108 m
969 paleo-surfaces, allow the identification of these paleo-surfaces as the remnant coastal terrace
970 of the MIS 9 highstand, tectonically dislocated (Figure 11 and 15). The subrounded
971 morphology, the medium to coarse grain-size and the high degree of sorting of the sand
972 deposits at Riserva Carpineto (RSC) clearly indicate that the flat sectors at elevations ranging
973 71-79 m a.s.l. represent remnant parts of an alluvial coastal plain, stretching NW to SE parallel
974 to the present coastline (Figure 11 and 12a3). Crystal ages yielded by sample RSC-SA firmly
975 constrain the formation of this coastal plain within MIS 9 (see also Figure 16). The bedded
976 deposits of Campo di Carne (CDC), ranging from coarse sand to silty clay, are suggestive of a

977 coastal alluvial plain, overlain by a transgressive backbeach deposit forming a wide dune
 978 ridge system culminating at ca. 85 m a.s.l. in this area (Figure 11 and 12a3), and equivalent to
 979 that occurring in Trigoria (TRIG) at analogous elevations (Figure 11 and Figure 12a1).
 980 Evidence from the Tenuta Monte di Leva (TML) site shows that this backbeach setting
 981 homogeneously extends parallel to the paleo-coastline, but it is presently displaced to a ca. 20
 982 m higher elevation in this sector (Figure 15). Micromorphological analysis of the
 983 concretionary layer observed in the TML indicates that this massive horizon formed in
 984 alluvial to backbeach environment characterized by a water table close to the surface,
 985 consistent with the reconstructed paleogeographic conditions, which show that it was part of
 986 the coastal plain. The geologic substrate at TML is indeed identical to that at TRIG, apart from
 987 the larger thickness of the upper, aeolian sand horizon above the concretionary layer at the
 988 latter location, consistent with a post-depositional tectonic displacement between these two
 989 sectors and limited erosion at TML.



990
 991 Figure 15 - Palimpsestic reconstruction of the tectonic evolution of the coastal sector between
 992 the Tiber mouth and Anzio in the time span 365 ka (age of emplacement of the Villa Senni
 993 Eruption Unit during lowstand of MIS 10) and 240 ka (onset of MIS 7.5). a) A regional collapse
 994 immediately following emplacement of the pyroclastic flow-deposit is inferred from the
 995 elevation gain between the top surface of aggradational successions of MIS 11 and MIS 9.
 996 MIS 11. b) Erosion of the original paleo-surface occurs during the lowstand of MIS 10, 360
 997 through 350 ka. c) Fluvial and coastal incisions are filled by sediment-aggradation during
 998 glacial termination V (335 ka) at the onset of the sea-level rise during MIS 9, and a coastal

999 setting including a beach to backbeach and coastal plain environment forms during the MIS 9
1000 highstand (325 ka). d) This homogeneous coastal setting is disrupted by fault displacement
1001 forming a structural height in the TML and a collapsed sector (Ardea basin) during the time
1002 span 320-240 ka (MIS 7.5 highstand) as indicated by the upper chrono-morphological
1003 constraint represented by the inner edges of MIS 7.5 coastal terrace (see text for further
1004 explanation).
1005

1006 On the other hand, the 98-108 m paleo-surface represents a striking geomorphological anomaly
1007 bordering the Ardea Basin to the NW (see also Figure 4), and is clearly interpretable as the
1008 result of differential uplift at the footwall of a boundary fault of the half-graben structure
1009 (Figure 11 and 15). Also the different geologic substrate that characterizes the 71-79 m paleo-
1010 surface within the Ardea Basin (e.g., VTB), which is formed by volcanic deposits (i.e.: the same
1011 substrate as the inland portion of the 98-108 m paleo-surface in VCR 1-2), is suggestive of
1012 tectonic lowering following the formation of a homogeneous coastal platform during the
1013 highstand of MIS 9, throughout this region. In contrast, in the case of a pre-existing
1014 embayment in this area, the 71-79 m paleo-surface at VTB should have had the same
1015 sedimentary substrate as that occurring in PC and RSC, confirming a coastal environment. In
1016 particular, the tectonic collapse of the Ardea Basin is constrained between 320 ka (end of the
1017 MIS 9 highstand) and 240 ka (highstand of MIS 7.5) (Figure 15), as provided by the geometry
1018 of the 60-67 m and 51-57 m coastal terraces, indicating that an embayment formed by the
1019 time of establishment of the new coastline during MIS 7.5 through MIS 7.1 (see Figure 3 and
1020 4). Remarkably, this time span is coincident with the occurrence of the Monte delle Fate phase
1021 of activity at the Colli Albani Volcanic district (Gaeta et al., 2016, and references therein).
1022

1023 **5.4 MIS 7.5 paleo-surface**

1024 The secure correlation with MIS 9 for the coastal plain deposits of the 71-79 m paleosurface,
1025 combined with previous geochronologic constraints that frame the 51-57m paleosurface
1026 within the broad MIS 7.5 - MIS 7.1 interval (Figure 16a), suggests that the intermediate 61-67
1027 m surface should be correlated with the early interglacial 7.5, while the paleo-surface
1028 occurring a few meters below, at an elevation of 51-57 m, should be correlated with the later
1029 isotopic peaks 7.3/7.1 which are not separated by a marked sea-level fall (See Figure 16a),
1030 and can be regarded as a single eustatic event. Crystal age distribution yielded by sample CR3
1031 from Colle Rotondo supports this correlation (Figure 16b). Based on the considerations
1032 reported above on the errors associated with the $^{40}\text{Ar}/^{39}\text{Ar}$ dating and their direct relation
1033 with grain-size, we can infer that an alluvial coastal plain formed by 249.3 ± 3.4 ka, an age
1034 remarkably coincident with glacial termination III at the onset of MIS 7.5 (Figure 16b), at ca.

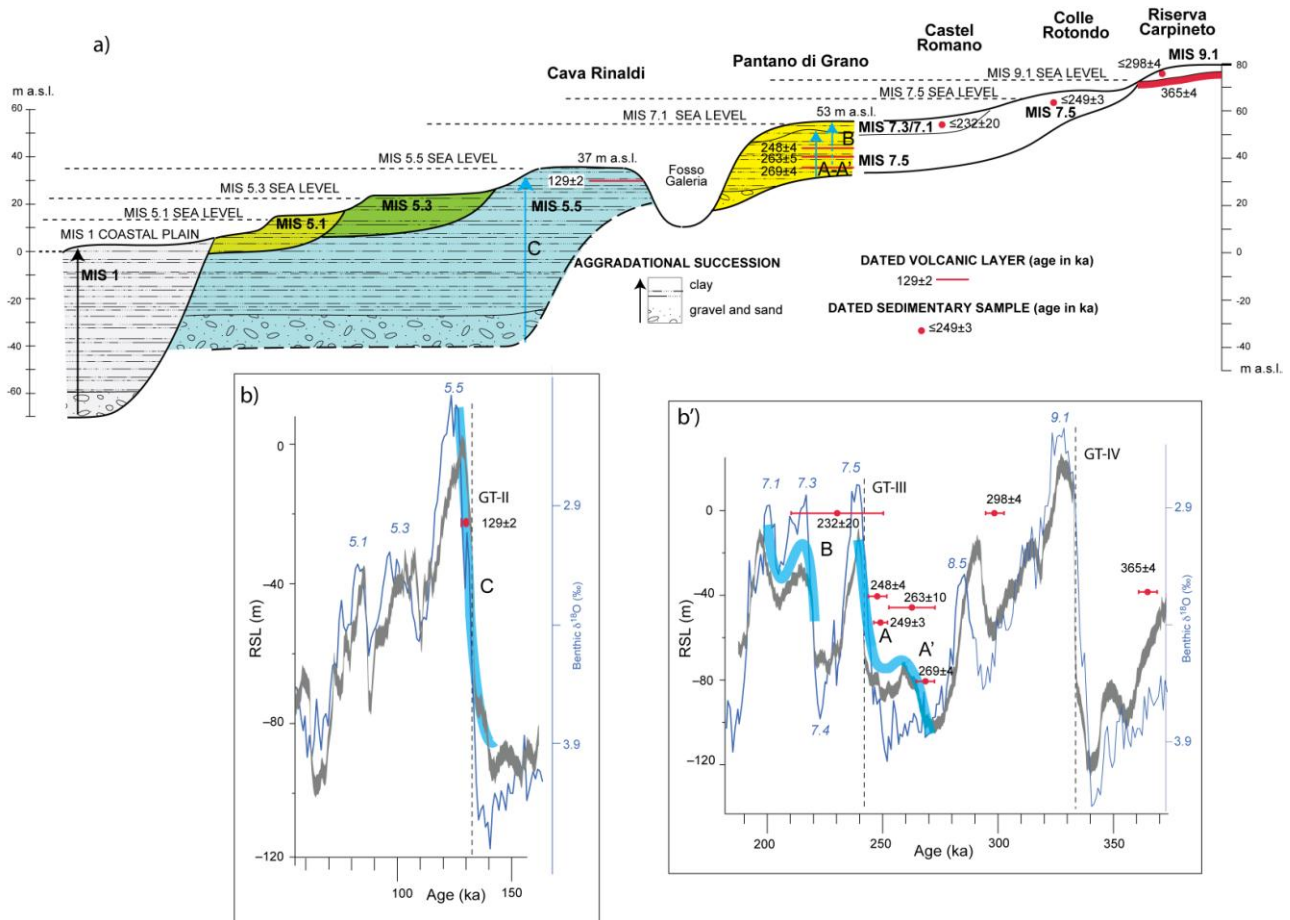
1035 60 m a.s.l.. It was successively mantled by a wind-blown deposit derived from the nearby
1036 beach during the interval 200 - 170 ka, a time when the coastline rebounded to the elevation
1037 of 60 m a.s.l. during sea-level high stands linked with the double peak in the isotopes curve of
1038 MIS 7.3 and 7.1. Indeed, according to geomorphologic reconstruction, sedimentologic
1039 features, and micromorphologic analysis, the Colle Rotondo sand is a backbeach deposit. The
1040 sand grains originated mainly from very proximal aeolian transport from the beach, where
1041 the original sediment accumulated after being eroded and transported by the Tiber River and
1042 its tributaries (A in Figure 14a). Moreover, since formation of the dune ridge, more aeolian
1043 material, as well as primary, air-fallen volcanic deposits (including sanidine minerals, B in
1044 Figure 14a), accumulated above it. Eventually, this sector was isolated from the coastal
1045 environment by the continued uplift, and it was affected only by deposition of the syn-
1046 eruptive fallout deposit of the Baccano unit at 132 ± 2 ka. If we consider the strong uplift of
1047 more than 50 m that occurred from 250 ka, the wind-blown depositional mechanism rapidly
1048 became ineffective, due to the increased elevation and distance from the coastline (e.g., by 125
1049 ka, Figure 14b). The regional uplift, determining the deep incision of the coastal terrace
1050 through the action of fluvial erosion, also generated the canyon-like morphology that
1051 characterizes this area, isolating the Colle Rotondo plateau and preventing alluvial
1052 sedimentation on its top (Figure 14c-d). Therefore, it is reasonable to assume that a very
1053 limited thickness of sediment accumulated above the original paleo-surface representing the
1054 coastal terrace, mainly by the air-fall mechanism and only subordinately, as a consequence of
1055 re-mobilization of pre-existing sediment, through wind transport, or water run-off and
1056 colluviation from the upper part of the plateau towards the lower sectors (C in Figure 14b). If
1057 we consider that the elevation gain between the top and the margins of the Colle Rotondo
1058 plateau is less than 4 m (Figure 14d), the latter depositional mechanisms must have acted in a
1059 very limited way.

1060

1061 **5.5 MIS 7.3-7.1 paleo-surface**

1062 The 51-57 m paleo-surface previously detected by Marra et al. (2016) has widespread
1063 expression at Ponte Galeria (Fig. 2), where chronostratigraphic constraints on the underlying
1064 aggradational deposits (Vitinia Formation, Luberti et al., 2017 and references therein) and
1065 their geometric/stratigraphic relationship with the 36 m terrace unambiguously provide
1066 correlation with the four-stepped sea-level rise that characterized MIS 7 (Marra et al., 2016b).
1067 In particular, an early aggradational phase of the Vitinia Formation around 269 ka matches
1068 the initial sea-level rise (A' in Fig. 16b) preceding the marked sea-level jump of glacial

1069 termination III that occurred at 240 ka, with which in turn is associated the main
 1070 aggradational succession of MIS 7.5, bracketed by post-queam ages of 253 ± 8 ka and 248 ± 4 ka
 1071 (A in Fig. 16b).



1072
 1073 Figure 16 - a) Idealized cross-section reconstructing the terraced deposits and the
 1074 corresponding aggradational successions in the investigated coastal sector, showing the
 1075 geochronologic constraints providing correlation with MIS 9.1 through MIS 5.5. b-b') Ages of
 1076 the dated volcanic deposits and reworked crystal populations (red dots, bars indicate the
 1077 analytical error at 2σ) are compared with the Oxygen isotope curve (Lisiecki and Raymo,
 1078 2005) and the Relative Sea Level (RSL) curve (Grant et al., 2014). Correspondence of sediment
 1079 aggradation with phases of rapid sea-level rise (thick blue lines) during glacial terminations
 1080 (GT) is highlighted.

1081
 1082 Finally, a marked unconformity cuts the deposits of MIS 7.5 aggradational succession and is
 1083 overlain by a new aggradational succession that represents the deposit forming the flat top of
 1084 the hills constituting the relict paleo-surface of 56-52 m a.s.l. The intervening erosional phase
 1085 and the following sediment aggradation evidently match the sea-level fall of MIS 7.4 and the
 1086 successive two-stepped sea-level rise of MIS 7.3 - MIS 7.1 (Marra et al., 2016b; B in Fig. 16b).
 1087 This observation corroborates the new assessment of the 51-57 m paleo-surface, and its
 1088 attribution to the later stages of MIS 7.3/7.1, rather than to MIS 7.5, as shown by correlation
 1089 provided in cross-section of Figure 16a).

1090

1091 **5.6 MIS 5.5 - 5.3 - 5.1 terraces**

1092 The occurrence of a suite of three lowest coastal terraces has been shown by geomorphologic
1093 reconstruction of their relict surfaces provided by Marra et al. (2016a, 2019a), who also
1094 demonstrated that three distinct successions of coastal plain sediments, corresponding to
1095 three coastlines at circa 34, 24 and 12 m a.s.l., are associated with these terraces (Figure 16a).
1096 The $^{40}\text{Ar}/^{39}\text{Ar}$ age of 129 ± 1 ka on a pyroclastic-flow deposit intercalated within the
1097 aggradational succession forming the 36 m terrace at Cava Rinaldi (Epi-Tyrrhenian
1098 Formation, Marra et al., 2015) demonstrated correlation with the MIS 5.5 highstand of 125 ka
1099 (Figure 16b'). The two lower terraces at 26 and 16 m were therefore tentatively correlated
1100 with the sea-level highstands of MIS 5.3 and 5.1, respectively. However, an intervening
1101 tectonic collapse of ca. 10 around 100 ka, interrupting a steady uplift phase between 250 ka
1102 and the Holocene had to be invoked by Marra et al. (2016a), in order to reconcile elevation of
1103 the terrace at 26 m with absolute sea-level established for MIS 5.3 and 5.1 in the literature
1104 (e.g. Rohling et al., 2009). A discussion of the age of these terraces is beyond the scopes of the
1105 present paper, and further geochronologic and sedimentologic investigations of these
1106 youngest successions are in progress, aimed at verifying their exact correlation with the MIS
1107 timescale. However, in the present study we have found an excellent fit of the new
1108 geomorphological and statistical assessment of these paleo-surfaces with the previous results
1109 of Marra et al. (2016a, 2019a), and we maintain preliminary correlation with the three marine
1110 isotopes' sub-stages of MIS 5.5, 5.3, and 5.1 in the discussion of the tectonic uplift.

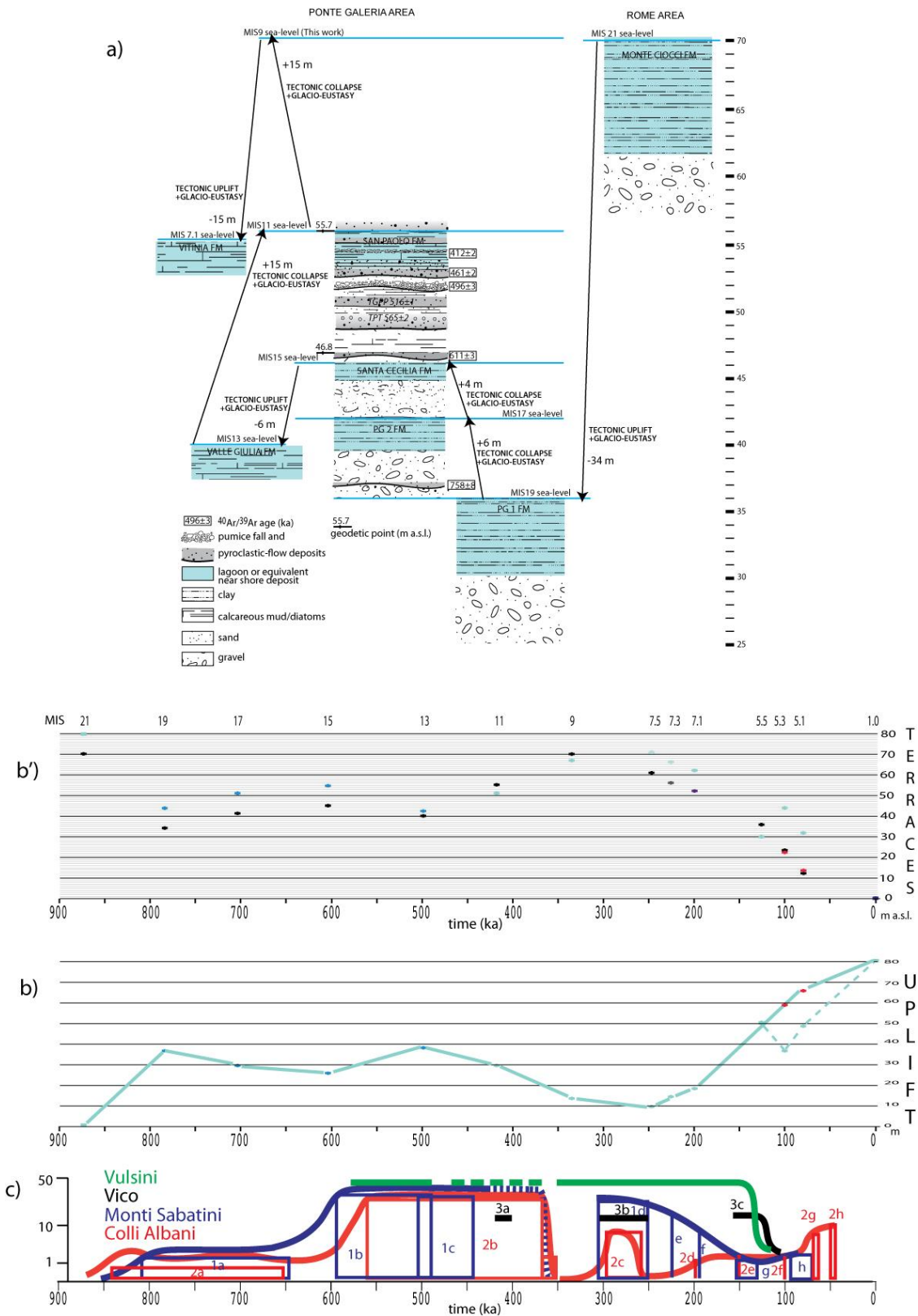
1111

1112 **5.7 Tectonic implications**

1113 All the sea-level markers provided by the aggradational successions of the Paleo-Tiber River
1114 correlated with MIS 21 through MIS 1 from literature and from the present study are shown
1115 in Figure 17a. Differences in elevation among the different coastal deposits assumed as sea-
1116 level markers (green shading in Figure 17a) are the result of the intervening tectonic
1117 movement (uplift or collapse) combined with the difference in maximum sea-level at each
1118 interglacial (glacio-eustatic component). This latter element is estimated assuming a sea-level
1119 10 m lower than present during MIS 21 through MIS 15 (blue crosses in Figure 17b') based on
1120 previous literature (Marra et al., 2016 and references therein), while values estimated in
1121 Rohling et al. (2009) are considered for MIS 13 through MIS 5.1 (green crosses).

1122

1123



1124

1125 Figure 17 - a) Synoptic representation of the different sections from the Rome area indicating
 1126 the aggradational successions and related sea-level indicators correlating with MIS 21
 1127 through MIS 7, integrating geochronologic and stratigraphic data from Karner and Renne,
 1128 1998; Karner and Marra, 1998; Karner et al., 2001b; Marra et al., 1998; 2016b; 2017a.
 1129

1130 Alternative values for MIS 5.3 and 5.1 (red crosses) are also used to assess the uplift curve for
1131 the last 125 ka, based on the assumption of a more reliable uniform tectonic uplift in this time
1132 span, and on recently provided geochronologic and geomorphologic constraints on the
1133 related sea-level markers (Marra et al., 2016a, 2019a). Once the correction for the glacio-
1134 eustatic component is applied, the cumulative uplift curve of Figure 17b is obtained. Similar to
1135 previous work (Marra et al., 2016a, 2019b), comparison between the uplift curve and the
1136 eruptive histories of the volcanic districts of the Roman Province is also provided (Figure
1137 17c). In comparison with previous reconstructions (e.g., Marra et al., 2016a) this refined uplift
1138 curve displays a marked subsidence phase between 500 and 300 ka, as provided by
1139 assessment of the MIS 9 sea-level markers at ca. 70 m a.s.l. established in the present work
1140 (Figure 17a). This fact reinforces the coupling already noted with the occurrence of two major
1141 phases of common volcanic activity at Colli Albani and Monti Sabatini 850 through 650 and
1142 600 through 350 ka. In particular, uplift coincides with the onset of these phases, while
1143 subsidence characterizes the eruptive time spans. The subsidence phase continued until 250
1144 ka and also encompasses the climax phase that, after a ca. 50 kyr dormancy, occurred at
1145 Vico, Monti Sabatini and Colli Albani, spanned the interval 320 - 250 ka, during which a
1146 rejuvenation of the volcanic activity occurred in all the districts of central Italy (Marra et al.,
1147 2004). The geochronologic constraints provided here for the MIS 7.5 and MIS 7.3/7.1 terraces
1148 allow a better definition of the beginning of the most recent uplift phase post-250 ka, which is
1149 characterized by an initial low gradient followed by a steady, steep increase 200 through 80 ka,
1150 and by a waning trend until the present (solid green curve in Figure 17b). As previously
1151 noted, this new uplift phase heralds and accompanies the latest volcanic phases during 90 - 70
1152 ka at Monti Sabatini and 70-36 ka at Colli Albani, and it has been suggested to be related to the
1153 onset of a new magmatic phase extending from southern Latium to the Campanian districts of
1154 Phlegraean Fields and Vesuvius (Mara et al., 2016a). In contrast, volcanic activity seems to
1155 have been extinguished in the districts of northern Latium (Vulsini, Vico) since 100 ka.
1156 However, Marra et al. (2019a) have shown that this recent uplift phase has affected the whole
1157 coast of Latium homogeneously, in apparent conflict with the lack of a new magmatic phase at
1158 these volcanoes. In contrast, cessation of the activity at Vulsini and Vico matches the sudden
1159 tectonic collapse which is inferred when the current sea-level values for MIS 5.3 and 5.1 are
1160 assumed (dashed portion of the uplift curve in Figure 17c). However, a direct link between
1161 local volcanic activity in the northern sector and the global tectonic signal in this region is
1162 unlikely. Moreover, recent geochronologic and geomorphologic data strongly imply that
1163 anomalous sea-levels characterized the MIS 5.3 and MIS 5.1 highstands in the Mediterranean

1164 region, suggesting the unforeseen role played by Glacial Isostatic Adjustment (GIA) on regional
1165 tectonics during the the post-glacial period (Marra et al., 2019a).
1166 Future investigation is needed in order to understand this complex framework of vertical
1167 movement, volcanic activity and glacio-eustasy affecting the Tyrrhenian Sea Margin during
1168 the last million years. Indeed, we note that beyond the common assumption of a
1169 interconnection between subduction, volcanism and regional uplift in the back-arc domain of
1170 the central Apennines (e.g., Conticelli and Peccerillo 1992), no dedicated study aimed at
1171 evaluating the geodynamic and isostatic forces responsible for the observed tectonic uplift
1172 has been undertaken so far.

1173

1174 **6. Conclusions**

1175 Combined geomorphologic study and statistical analysis, together with review and re-
1176 analyses of previous published data, have allowed us to identify a set of paleo-surfaces
1177 defined by discrete classes of elevation for topographic culminations in the coastal
1178 Tyrrhenian Sea sector of central Latium.

1179 We recognized eight such paleo-surfaces defined by the elevation ranges: 98-108, 80-89, 71-
1180 79, 61-67, 51-57, 30-43, 22-27, 11-17 m a.s.l..

1181 The three lowest paleo-surfaces are narrowly elongated parallel to the coastline and were
1182 identified through definition of the corresponding sea-level markers and geochronologic
1183 constraints in previous studies as the marine terraces of MIS 5.5, 5.3 and 5.1, (Marra et al.,
1184 2016a, 2019a).

1185 The highest five paleo-surfaces have been investigated here and their physical extension has
1186 been validated through DEM analyses, in order to compare the results of the
1187 geomorphological study on 1:25.000 topographic maps.

1188 The sedimentologic-stratigraphic features of the soils and of the sedimentary deposits
1189 forming these paleo-surfaces have been investigated in order to define their paleogeographic
1190 context and to identify the sea-level markers for those which have been interpreted as
1191 remnant portions of coastal terraces.

1192 $^{40}\text{Ar}/^{39}\text{Ar}$ ages of detrital sanidine extracted from the sandy deposit of the recognized coastal
1193 terraces has allowed us to correlate the 71-79 m, the 61-67 m, and the 51-57 m paleo-surfaces
1194 with the coastal terraces formed during the MIS 9.1, MIS 7.5, and MIS 7.3/7.1 highstands,
1195 respectively.

1196 Paleogeographic reconstruction has allowed us to interpret the 71-79 m, 80-89 m, and 98-108
1197 m paleo-surfaces as a single tectonically displaced, widespread coastal platform formed during
1198 the MIS 9.1 highstand.

1199 Based on the combination of our refined dataset of terrace elevations with published data on
1200 relative elevation of maximum sea level during the highstands of MIS 21 through MIS 5.1, we
1201 assess the regional uplift curve in the last 900 ka and recognize the occurrence of a climactic
1202 extensional tectonic phase affecting this coastal sector between 320 and 240 ka, coincident
1203 with occurrence of the Monte delle Fate phase of activity at the Colli albani Volcanic district.

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1207 **Supplementary Material #1**- 1:25.000 basemap with topographic culminations
1208 **Supplementary Material #2A**: Micromorphology: Methods - Fig. S1-S6
1209 **#2B**: X-Ray power diffraction methods **#2C**: SEM microphotographs - Fig. S7
1210 **Supplementary Material #2D** - Diffractograms
1211 **Supplementary Material #3a, b**: Full $^{40}\text{Ar}/^{39}\text{Ar}$ data.
1212
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1214 REFERENCES

1215

1216

1217 Barberi, F., Buonasorte, G., Cioni, R., Fiordelisi, A., Foresi, L., Iaccarino, S., Laurenzi, M.A.,
1218 Sbrana, A., Vernia, L., Villa, I.M., 1994. Plio-Pleistocene geological evolution of the geothermal
1219 area of Tuscany and Latium. Mem. Descr. Carta Geol. d' It. 49, 77-134

1220

1221 Bridgland, D.R., Westaway, R., 2008. Climatically controlled river terrace staircases: a
1222 worldwide Quaternary phenomenon, *Geomorphology* 98, 285–315.

1223

1224 Cioni, R., Sbrana A., Bertagnini, A., Buonasorte G., Landi, P., Rossi, U., Salvati, L., 1987. Laurenzi,
1225 M.A., Tephrostratigraphic correlations in the Vulsini, Vico and Sabatini volcanic successions.
1226 *Periodico di Mineralogia* 56, 137-155.

1227

1228 Conticelli, S., Peccerillo, A., 1992. Petrology and geochemistry of potassic and ultrapotassic
1229 volcanism in central Italy: petrogenesis and inferences on the evolution of the mantle sources,
1230 *Lithos* 28, 221-240.

1231

1232 De Rita, D., Funicello, R., Rossi, U., Sposato, A., 1983. Structure and evolution of the Sacrofano-
1233 Baccano caldera, Sabatini Volcanic Complex, Rome: *J. Volcanol. Geotherm. Res.* 17, 219-236.

1234

1235 De Rita, D., Faccenna, C. Funicello, R. Rosa, C., 1995. Stratigraphy and volcano-tectonics, in *The*
1236 *Volcano of the Alban Hills*, edited by R. Trigila, Università degli Studi di Roma "La Sapienza",
1237 Roma, 33–71.

1238

1239 Everdin, J.F., Curtis, G., 1965. The potassium-argon dating of Late Cenozoic rocks in East Africa
1240 and Italy. *Current Anthrop.*, 6, 343-369.

1241

1242 Faccenna, C., Funicello R., Bruni A., Mattei A., Sagnotti L., 1994. Evolution of a transfer-related
1243 basin: the Ardea Basin (Latium, Central Italy). *Basin Research* 5, 12-11.

1244

1245 Farr, T. G., Hensley, S., Rodriguez, E., Martin, J., Kobrick, M., 2000. The Shuttle Radar
1246 Topography Mission, Proceedings of a Conference held 26-29 October 1999, Toulouse, France.
1247 European Space Agency, 2000. ESA-SP vol. 450, ISBN: 9290926414, p.361.

1248

1249 Ferranti, L., Antonioli, F., Mauz, B., Amorosi, A., Dai Pra, G., Mastronuzzi, G., Monaco, C., Orrù,
1250 P., Pappalardo, M., Radtke, U., Renda, P., Romano, P., Sansò, P., Verrubbi, V., 2006. Markers of
1251 the last interglacial sea-level high stand along the coast of Italy: Tectonic implications.
1252 *Quaternary International* 145/146, 30-54.

1253

1254 Freda, C., Gaeta, M., Palladino, D. M., Trigila, R., 1997. The Villa Senni Eruption (Alban Hills,
1255 Central Italy): the role of H₂O and CO₂ on the magma chamber evolution and on the eruptive
1256 scenario. *Journal of Volcanology and Geothermal Research* 78, 103-120.

1257

1258 Gaeta, M., Freda, C., Marra, F., Arienzo, I., Gozzi, F., Jicha, B., Di Rocco, T., 2016. Paleozoic
1259 metasomatism at the origin of Mediterranean ultrapotassic magmas: constraints inferred
1260 from time-dependent geochemistry of volcanic products from Colli Albani (Central Italy),
1261 *Lithos*, 244, 151-164. <http://dx.doi.org/10.1016/j.lithos.2015.11.034>

1262

1263 Gatta, M., Giaccio, B., Marra, F., Rolfo, M.F., 2017. Trace-element fingerprinting of the 69–36 ka
1264 Colli Albani eruptive units: A preliminary dataset for archaeological and tephra studies in
1265 central-southern Italy. *Journal of Archaeological Science: Reports*, 16, 330-340.
1266
1267 Giaccio, B., Marra, F., Hajdas, I., Karner D.B., Renne, P.R., Sposato A., 2009. $^{40}\text{Ar}/^{39}\text{Ar}$ and ^{14}C
1268 geochronology of the Albano maar deposits: implications for defining the age and eruptive
1269 style of the most recent explosive activity at the Alban Hills Volcanic District, Italy. *Journal of*
1270 *Volcanology and Geothermal Research* 185, 203-213.
1271
1272 Giaccio, B., Niespolo, E., Pereira, A., Nomade, S., Renne, P.R., Alber, P.G., Arienzo, I., Regattieri,
1273 Wagner, B., Zanchetta, G., Gaeta, M., Galli, P., Mannella, G., Peronace, E., Sottili, G., Florindo, F.,
1274 Leicher, N., Marra, F., Tomlinson, E.L., 2017. First integrated tephrochronological record for
1275 the last ~190 kyr from the Fucino Quaternary lacustrine succession, central Italy. *Quaternary*
1276 *Science Reviews* 158, 211-234. <http://dx.doi.org/10.1016/j.quascirev.2017.01.004>
1277
1278 Giordano, G., De Benedetti, A.A., Diana, A., Diano, G., Gaudioso, F., Marasco, F., Miceli, M., Mollo,
1279 S., Cas, R.A.F., Funiciello, R., 2006. The Colli Albani mafic caldera (Roma, Italy): stratigraphy,
1280 structure and petrology, *J. Volcanol. Geotherm. Res.*, 155, 49–80.
1281
1282 Grant, K.M., Rohling, E.J., Bronk Ramsey, C., Cheng, H., Edwards, R.L., Florindo, F., Heslop, D.,
1283 Marra, F., Roberts, A.P., Tamisiea, M.E., Williams, F., 2014. Sea-level variability over five glacial
1284 cycles. *Nature Communications* 5, 5076. doi:10.1038/ncomms6076
1285
1286 Jicha, B.R., Singer, B.S., Sobol, P. 2016. Re-evaluation of the ages of $^{40}\text{Ar}/^{39}\text{Ar}$ sanidine
1287 standards and supereruptions in the western U.S. using a Noblesse multi-collector mass
1288 spectrometer. *Chemical Geology* 431, 54–66.
1289
1290 Karner, D.B., Marra, F., 1998. Correlation of fluviodeltaic aggradational sections with glacial
1291 climate history: A revision of the Pleistocene stratigraphy of Rome. *Geological Society of*
1292 *America Bulletin* 110, 748-758.
1293
1294 Karner, D.B., Marra, F., Florindo, F., Boschi, E., 2001a. Pulsed uplift estimated from terrace
1295 elevations in the coast of Rome: Evidence for a new phase of volcanic activity? *Earth and*
1296 *Planetary Science Letters* 188, 135-148.
1297
1298 Karner, D.B., Marra, F., Renne, P.R., 2001b. The history of the Monti Sabatini and Alban Hills
1299 volcanoes: groundwork for assessing volcanic-tectonic hazards for Rome. *J. Volc. and Geoth.*
1300 *Res.* 107: 185-215.
1301
1302 Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed
1303 benthic $\delta^{18}\text{O}$ records. *Paleoceanography* 20, PA1003. doi:10.1029/2004PA001071.
1304
1305 Luberti, G.M., Marra, F., Florindo, F., 2017. A review of the stratigraphy of Rome (Italy)
1306 according to geochronologically and paleomagnetically constrained aggradational
1307 successions, glacio-eustatic forcing and volcano-tectonic processes. *Quaternary International*.
1308 <http://dx.doi.org/10.1016/j.quaint.2017.01.044>
1309
1310 Malinverno, A., Ryan, W.B.F., 1986. Extension in the Tyrrhenian sea and shortening in the
1311 Apennines as results of arc migration driven by sinking of the lithosphere. *Tectonics* 5, 227-
1312 245.

1313
1314 Mariucci, M.T., S. Pierdominici, F. Marra, P. Montone, L. Pizzino, 2008. Looking into a volcanic
1315 area: an overview on the 350m scientific drilling at Colli Albani (Rome, Italy). J. Volcanol.
1316 Geotherm. Res., doi:10.1016/j.jvolgeores.2008.04.007.
1317
1318 Marra, F., Florindo, F., Boschi E., 2008. The history of glacial terminations from the Tiber River
1319 (Rome): insights to glacial forcing mechanisms, *Paleoceanography*, 23, PA2205,
1320 doi:10.1029/2007PA001543.
1321
1322 Marra F., Karner, D.B., Freda, C., Gaeta, M., Renne, P.R., 2009. Large mafic eruptions at the
1323 Alban Hills Volcanic District (Central Italy): chronostratigraphy, petrography and eruptive
1324 behavior. *Journ. of Volc. and Geoth. Res.* 179, 217-232. doi:10.1016/j.jvolgeores.2008.11.009
1325
1326 Marra, F., Sottili, G., Gaeta, M., Giaccio, B., Jicha, B., Masotta, M., Palladino, D.M., Deocampo, D,
1327 2014. Major explosive activity in the Sabatini Volcanic District (central Italy) over the 800-390
1328 ka interval: geochronological - geochemical overview and tephrostratigraphic implications,
1329 *Quaternary Science Reviews* 94, 74-101.
1330
1331 Marra, F., Ceruleo, P., Jicha, B., Pandolfi, L. Petronio, Salari, L. , 2015. A new age within MIS 7
1332 for the *Homo neanderthalensis* of Saccopastore in the glacio-eustatically forced sedimentary
1333 successions of the Aniene River Valley, Rome. *Quaternary Science Reviews* 129, 260–274.
1334 doi:10.1016/j.quascirev.2015.10.027
1335
1336 Marra, F., Florindo, F., Anzidei, M., Sepe, V., 2016a. Paleo-surfaces of glacio-eustatically forced
1337 aggradational successions in the coastal area of Rome: assessing interplay between tectonics
1338 and sea-level during the last ten interglacials. *Quaternary Science Review*, 148, 85-100.
1339 <http://dx.doi.org/10.1016/j.quascirev.2016.07.003>
1340
1341 Marra, F., Rohling, E.J., Florindo, F., Jicha, B., Nomade, S., Pereira, A., Renne., P.R., 2016b.
1342 Independent $^{40}\text{Ar}/^{39}\text{Ar}$ and ^{14}C age constraints on the last five glacial terminations from the
1343 aggradational successions of the Tiber River, Rome (Italy). *Earth Planet Sci Lett.* in press.
1344
1345 Marra, F., Gaeta, M., Giaccio, B., Jicha, B., Palladino, D., Polcari, M., Sottili, G., Taddeucci, J.,
1346 Florindo, F., Stramondo, S., 2016c. Assessing the volcanic hazard for Rome: $^{40}\text{Ar}/^{39}\text{Ar}$ and In-
1347 SAR constraints on the most recent eruptive activity and present-day uplift at Colli Albani
1348 Volcanic District, *Geophys. Res. Lett.* 43, 6898–6906. doi:10.1002/2016GL069518.
1349
1350 Marra, F., Florindo, F., Petronio, C., 2017. Quaternary fluvial terraces of the Tiber Valley:
1351 geochronologic and geometric constraints on the back-arc magmatism-related uplift in central
1352 Italy. *Journal Scientific Reports* 7: 2517. DOI:10.1038/s41598-017-02437-1
1353
1354 Marra, F., Petronio, C., Salari, L., Florindo, F., Giaccio, B., Sottili, G., 2018a. A review of the
1355 Villafranchian fossiliferous sites of Latium in the framework of the geodynamic setting and
1356 paleogeographic evolution of the Tyrrhenian Sea margin of central Italy, *Quaternary Science*
1357 *Reviews* 191, 299-317. 10. 1016/ j. quascirev. 2018. 05. 011
1358
1359 Marra, F., Petronio, C., Ceruleo, P., Di Stefano, G., Florindo, F., Gatta, M., La Rosa, M., Rolfo, M.F.,
1360 Salari, L., 2018b. The archaeological ensemble from Campoverde (Agro Pontino, central Italy):
1361 new constraints on the Last Interglacial sea level markers. *Scientific Reports*, SREP-18-23649,
1362 DOI : 10.1038/s41598-018-36111-x

1363
1364 Marra F., Nomade S., Pereira A., Petronio C., Salari L., Sottili G., Bahain J.J., Boschian G., Di
1365 Stefano G., Falgueres C., Florindo F., Gaeta M. Giaccio B., Masotta M., 2018c. A review of the
1366 geologic sections and the faunal assemblages of Aurelian Mammal Age of Latium (Italy) in the
1367 light of a new chronostratigraphic framework. *Quaternary Science Reviews* 181, 173-199.
1368 doi.org/10.1016/j.quascirev.2017.12.007
1369
1370 Marra, F., Bahain, J.-J., Jicha, B., Nomade, S., Palladino, D.M., Pereira, A., Tolomei, C., Voinchet,
1371 P., Anzidei, M., Aureli, D., Ceruleo, P., Falguères, C., Florindo, F., Gatta, M., Ghaleb, B., La Rosa,
1372 M., Peretto, C., Petronio, C., Rocca, R., Rolfo, M.F., Salari, L., Smedile, A., Tombret, O., 2019a.
1373 Reconstruction of the MIS 5.5, 5.3 and 5.1 coastal terraces in Latium (central Italy): a re-
1374 evaluation of the sea-level history in the Mediterranean Sea during the Last Interglacial,
1375 *Quaternary International*.
1376
1377 Marra, F., Florindo, F., Jicha, B.R., Nomade, S., Palladino, D.M., Pereira, A., Sottili, G., Tolomei, C.,
1378 2019b. Assessing volcano-tectonic hazard of the Monti Sabatini Volcanic District on the city of
1379 Rome (central Italy): evidence from new geochronologic constraints on the Tiber River MIS 5
1380 terraces, *Scientific Reports*, in press.
1381
1382 Masotta, M., Gaeta, M., Gozzi, F., Marra, F., Palladino, D.M., Sottili, G., 2010. H₂O- and
1383 temperature-zoning in magma chambers: the example of the Tufo Giallo della Via Tiberina
1384 eruptions (Sabatini Volcanic District, central Italy). *Lithos* 118, 119-130.
1385
1386 Nicoletti, M., 1969. Datazioni argon-potassio di alcune vulcaniti delle regioni vulcaniche
1387 Cimina e Vicana. *Per. Mineral.*, 38, 1-20.
1388
1389 Nisi, M.F., Antonioli, F., Dai Pra, G., Leoni, G., Silenzi S., 2003. Coastal Deformation between the
1390 Versilia and the Garigliano plains (Italy) derived from the elevations of the Last Interglacial
1391 stage, *Journal of Quaternary Science* 18, 709-721.
1392
1393 Palladino, D, Simej, S., Sottili, G., and Trigila, R., 2010, Integrated approach for the
1394 reconstruction of stratigraphy and geology of Quaternary volcanic terrains: An application to
1395 the Vulsini Volcanoes (central Italy), in *Stratigraphy and Geology of Volcanic Areas* (eds. G.
1396 GropPELLI, and L. Viereck-Goette), *The Geological Society of America Special Paper*, **464**, 63-84.
1397 doi: 10.1130/2010.2464(04).
1398
1399 Patacca, E., Sartori, R., Scandone, P., 1990. Tyrrhenian basin and apenninic arcs: kinematic
1400 relations since late Tortonian times. *Mem. Soc. Geol. It.* 45, 425-451.
1401
1402 Peccerillo, A., Frezzotti, M.L., 2015. Magmatism, mantle evolution and geodynamics at the
1403 converging plate margins of Italy. *Journal of the Geological Society*.
1404 <http://dx.doi.org/10.1144/jgs2014-085>
1405
1406 Pereira, A., Nomade, S., Falguères, C., Bahain, J.-J., Tombret, O., Garcia, T., Voinchet, P.,
1407 Bulgarelli, A.G., Anzidei, P., 2017. ⁴⁰Ar/³⁹Ar and ESR/U- series data for the La Polledrara di
1408 Cecanibbio archaeological site (Lazio, Italy). *Journal of Archaeological Science: Reports*, in
1409 press.
1410

1411 Perini, G., Francalanci, L., Davidson, J.P., and Conticelli, S., 2004, Evolution and genesis of
1412 magmas from Vico volcano, Central Italy: multiple differentiation pathways and variable
1413 parental magmas, *Journal of Petrology*, **45**, 139–182.
1414

1415 Rivera, T.A., Storey, M., Schmitz, M.D., Crowley, J.L., 2013. Age intercalibration of $^{40}\text{Ar}/^{39}\text{Ar}$
1416 sanidine and chemically distinct U/Pb zircon populations from the Alder Creek Rhyolite
1417 Quaternary geochronology standard. *Chemical Geology* 345, 87-98.
1418

1419 Rohling E.J., Grant, K., Bolshaw, M., Roberts, A.P., Siddall, M. Hemleben, Ch., Kucera, M., 2009.
1420 Antarctic temperature and global sea level closely coupled over the past five glacial cycles.
1421 *Nature Geoscience* 2, 500-504. DOI: 10.1038/NGE0557
1422

1423 Serri, G., Innocenti, F., Manetti, P., 1993. Geochemical and Petrological evidence of the
1424 subduction of delaminated Adriatic continental lithosphere in the genesis of the Neogene-
1425 Quaternary magmatism of Central Italy, *Tectonophysics* 223, 117-147.
1426

1427 Sevink, J., Di Vito, M.A., Piochi, M., Mormone, A., Van Gorp, V., Bakels, C., 2018. A rare Mid-
1428 Würmian lithoid tuff in the Agro Pontino graben (Southern Lazio, Italy) and its identification
1429 as an Albano 5-7 related distal tephra deposit (41-36 kaBP): characteristics, provenance and
1430 palaeogeographical implications. *Annals of Geophysics*, 61, 1, S109. DOI: 10.4401/ag-7534
1431

1432 Sottili, G., Palladino, D.M., Marra, F., Jicha, B., Karner, D.B., Renne, P., 2010. Geochronology of
1433 the most recent activity in the Sabatini Volcanic District, Roman Province, central Italy, *Journ.*
1434 *of Volc. and Geoth. Res.* 196, 20-30. DOI:10.1016/j.jvolgeores.2010.07.003
1435

1436 Sottili G., Palladino D.M., Zanon V., 2004. Plinian activity during the early eruptive history of
1437 the Sabatini Volcanic District, Central Italy. *J. Volcanol. Geotherm. Res.* 135, 361-379.
1438

1439 Villa, P., Pollarolo, L., Conforti, I., Marra, F., Biagioni, C., Degano, I., Lucejko, J.J., Tozzi, C.,
1440 Pennacchioni, M., Zanchetta, G., Nicosia, C., Panzeri, L., Martini, M., Sibilìa, E., From Neandertals
1441 to modern humans: New data on the Uluzzian. *Plos One* 13(5): e0196786.
1442 <https://doi.org/10.1371/journal.pone.0196786>
1443
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1 **MIS 9 to MIS 5 terraces along the Tyrrhenian Sea coast of Latium (central**
2 **Italy): assessing interplay between sea-level oscillations and tectonic**
3 **movements**

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17

18 **Abstract**

19 We present a review of the geomorphological ~~studies performed on~~ of the Tyrrhenian Sea
20 coast of central Italy integrated by a novel structural-geomorphological study coupled with
21 statistical analysis of topographic culminations and comparison with a Digital Elevation

22 Model ~~of the ground surface~~, aimed at reconstructing a suite of paleo-surfaces corresponding
23 to remnant portions of marine terraces. We performed geochronological, sedimentological,
24 micromorphological and mineralogical investigations on the deposits forming the different
25 paleo-surfaces ~~in the coastal area of central Italy comprised~~ between Civitavecchia and Anzio
26 town, in order to provide chronostratigraphical, paleogeographical and paleoenvironmental
27 constraints. Using the newly achieved dataset we correlate these paleo-surfaces with the
28 coastal terraces formed during past sea-level highstands, as recognized by previous studies,
29 and we refine their correlation with the Marine Isotope Stage (MIS) timescale.

30 In particular, we have extended our geomorphological analyses landward in the area between
31 the Tiber River mouth and Anzio, in order to include the oldest paleo-surface developed
32 above the deposits of the last large explosive eruption ~~occurred at~~ 365±4 ka ~~at-in~~ the Colli
33 Albani Volcanic District. Results of this study allow us to recognize a set of higher paleo-
34 surfaces at elevation ranging 108 to 71 m a.s.l., ~~that-which~~ we interpret as one
35 tectonically displaced, widespread coastal ~~paleomorphological setting terrace~~ originated
36 during the MIS 9.1 highstand. We correlate the previously identified paleo-surfaces of 66-62
37 m and 56-52 m with the equivalent coastal ~~setting terraces~~ developed during the sea-level
38 highstands of sub-stages 7.5 and 7.3/7.1. Moreover, based on data from literature ~~data~~ on

39 | relative elevation of maximum sea level during ~~the~~ highstands of MIS 11 through MIS 5.1, we
40 | assess the regional uplift and the concurrent tectonic displacements ~~that have~~ occurred since
41 | 900 ka in this area.

42

43 | **Keywords:** paleo-surface; coastal terrace; glacio-eustasy; regional uplift

44

45 | **Highlights:**

46 | We reconstruct a suite of six paleo-surfaces ~~on~~ along the central Tyrrhenian Sea coast

47 | Paleoenvironmental data identify these paleo-surfaces as remnants of coastal terraces

48 | We provide ⁴⁰Ar/³⁹Ar age constraints to the terraced sedimentary deposits

49 | We correlate these terraces with ~~highstands of~~ the Marine Isotope Stage ~~timescale~~ record

50 | We identify ~~the~~ previously unrecognized MIS 9 sea-level markers in this region

51 | We assess ~~the~~ regional uplift and ~~the~~ tectonic displacements in the last 400 ka

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55 1. Introduction

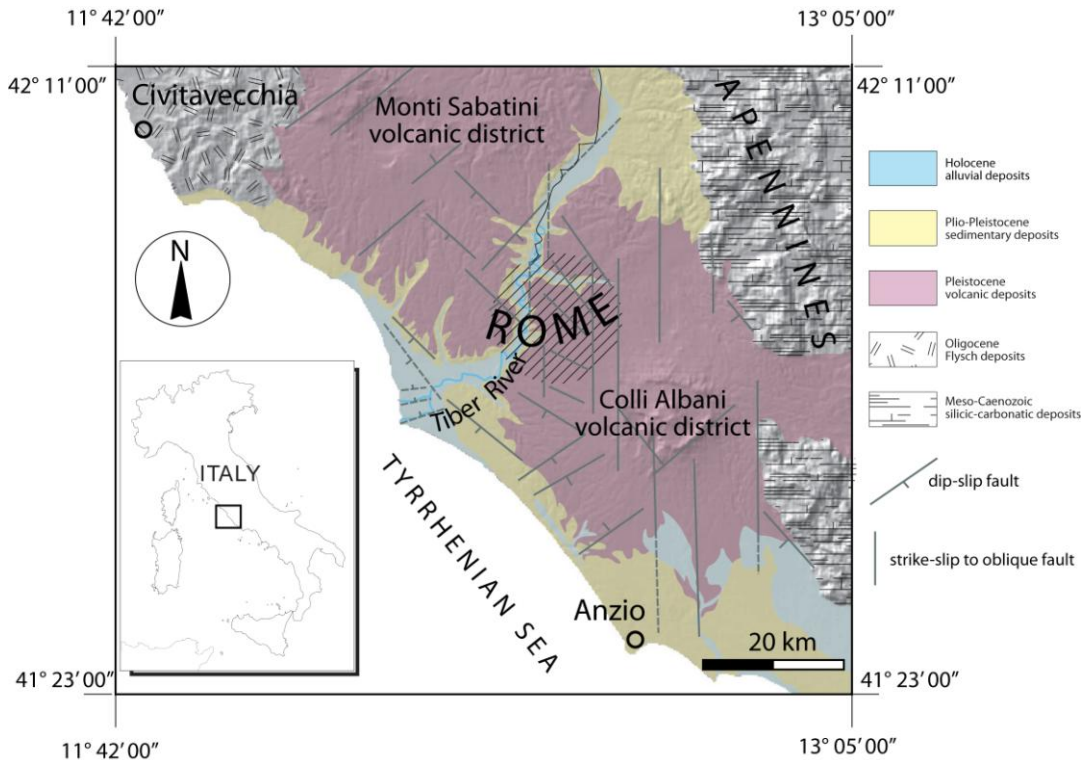
56 The Tyrrhenian Sea coast of Latium (Figure 1) is part of a geodynamic domain characterized
57 by back-arc extensional processes (Malinverno and Tayan, 1986; Patacca et al., 1990) that
58 during Pleistocene times have lead to the origin-formation of an ultra-potassic chain of
59 volcanic districts (Serri et al., 1993; Conticelli and Peccerillo, 1992; Peccerillo and Frezzotti,
60 2015). Concurrent with the volcanic processes, regional uplift has caused the progressive
61 emersion-emergence of this area since the end of the Santerian (lower Calabrian), around 1.5
62 maMa, leading to widespread continentalization since ~1 ma-Ma (Barberi et al., 1994; Marra
63 et al., 2018a). The regional uplift along the Tyrrhenian coast of Latium has been interpreted as
64 driven by the subduction process and uprising of metasomatized magma bodies on the
65 Tyrrhenian Sea Margin of central Italy, superimposed on a smaller isostatic component of
66 uplift (Marra et al., 2017, and references therein). Two major pulses of uplift are recognized:
67 0.86 through 0.5 Ma, and 0.25 Ma through the Present (Marra et al., 2016a); as a result of this
68 overall uplifting regime, the continental, fluvial-lacustrine and coastal deposits in this area
69 formed a widespread pattern of terraces that, similar to other regions in the world (e.g.,
70 Bridgland and Westaway, 2008), are organized in a staircase geometry, with the oldest
71 surfaces at highest elevation.

72 Geographic extension and rates of the most recent phases of this uplift during Middle-~~Upper~~
73 Late Pleistocene have been assessed by a series of studies reconstructing a suite of coastal
74 terraces and correlating them with the sea-level highstands ~~of identified by~~ the Marine
75 Isotope Stage (MIS) timescale-record (e.g., Karner et al., 2001a; Nisi et al., 2003; Ferranti et al.,
76 2006). More recently, a re-evaluation of the geometry and the age of these terraces in the
77 coastal area comprised between the Argentario and Anzio promontories has been proposed
78 by means of an original geomorphological approach and the integration of new
79 geochronologic constraints provided by $^{40}\text{Ar}/^{39}\text{Ar}$ ages of volcanic layers intercalated within
80 the glacio-eustatically forced aggradational successions forming the terraced deposits in this
81 region (Marra et al., 2015; 2016a). Moreover, a new geomorphologic study coupled with
82 biochronologic constraints allowed Marra et al. (2018b, 2019a) to extend the reconstruction
83 of a complete suite of terraces in the coastal reach between Anzio and Circeo promontories,
84 and to propose their correlation with MIS 7.5 through MIS 5.1. In contrast, only a poorly
85 defined paleo-surface ranging 61-67 m a.s.l. has been dubitatively-dubiously assigned to the
86 MIS 9 terrace, ~~so far~~ (Marra et al., 2016a). Moreover, geochronologic constraints so far
87 provided to the local MIS 9 aggradational succession (Aurelia Formation, Karner and Marra,
88 1998) evidenced a remarkable anomaly, significantly pre-dating ~~the~~ glacial termination IV

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89 and the completion of MIS 9 highstand (Marra et al., 2016b). Therefore, assessing the
 90 geometry and providing time constraint ~~to~~on the deposits of the MIS 9 coastal terrace in this
 91 region may have notable implications ~~on~~for understanding the response to the global paleo-
 92 climatic signal and on the tectonic process acting on the Tyrrhenian Sea margin of central
 93 Italy.



94 11° 42' 00" 13° 05' 00"
 95 Figure 1 - DEM image of the Tyrrhenian Sea margin of central Italy showing the main
 96 structural features of the investigated area (after Acocella and Funicello, 2006; Frepoli et al.,
 97 2010).
 98

99 In the present paper we have refined the structural-geomorphological study in the previously
 100 investigated sector comprised between Civitavecchia and Anzio, and we have re-assessed the
 101 statistical analysis ~~on~~of the elevations of the paleo-surfaces correlated by Marra et al. (2016a,
 102 2019a) with the MISs. In particular, we have extended the geomorphological analysis
 103 landward, in order to include the oldest paleo-surface affecting the deposits of the last large
 104 eruption ~~occurred at~~in the Colli Albani Volcanic District (Villa Senni Eruption Cycle, 365±4 ka,
 105 Marra et al., 2009) in the area between the Tiber mouth and Anzio. Two huge pyroclastic-flow
 106 deposits emplaced during this eruption phase (Tufo Lionato and Pozzolanelle, Freda et al.,
 107 1995) ~~mantling~~mantle the surface with a volcanic cover ~~radially~~radially spreading radially as far as

108 50 km from the vent and reaching up to 20 m in thickness, locally (De Rita et al., 1995;
109 Giordano et al., 2006; Mariucci et al., 2008). Due to this pyroclastic cover, the paleo-surfaces
110 older than 365 ka are completely buried and no geomorphologic evidence is expected for
111 them in this area.

112 We performed chronostratigraphical, sedimentological, micromorphological, mineralogical
113 and petrographic investigations ~~on~~of the deposits forming the different paleo-surfaces in
114 order to provide geochronological, paleogeographical and paleoenvironmental constraints.
115 We used four $^{40}\text{Ar}/^{39}\text{Ar}$ age determinations on detrital sanidine crystals extracted from key
116 deposits in order to provide post-*quem* ages on the paleo-surfaces and relative chronologic
117 constraints for their correlation with the suite of coastal terraces recognized and
118 geochronologically constrained by previous studies, refining their correlation with the MIS
119 timescale.

120

121 **2. Geological Setting**

122 The study area is located on the Tyrrhenian Sea margin of central Italy (Figure 1).
123 Since the Middle Pleistocene the interplay between glacio-eustatic sea-level variations,
124 tectonic processes, sedimentation and volcanic activity has built the geological framework of
125 this area (Luberti et al., 2017, and references therein). During periods of sea-level fall, erosion
126 occurred, ~~while~~whereas deposition took place during phases of sea-level rise, filling
127 previously excavated incisions with a suite of aggradational successions (Karner and Marra,
128 1998; Marra et al., 2008). A thick succession of pyroclastic-flow deposits, from both the Colli
129 Albani and Monti Sabatini volcanic districts, and subordinated Sabatinian air-fall deposits,
130 interfingers with the continental sediments. After the last volcanic eruptions at 36 ka (Marra
131 et al., 2016c), the volcanic plateau was deeply incised during the Last Glacial, ~~also~~partly as a
132 consequence of the intervening regional uplift (Marra et al., 2016a). Eventually, the
133 paleovalleys were filled by fluvial deposits as a consequence of the sea-level rise after the last
134 glacial termination.

135

136 **3. Methods**

137 **3.1 Geomorphological analysis**

138 In the present study, paleo-surfaces have been mapped following the geomorphological
139 approach described in Marra et al. (2016a; 2017), based on the identification of a set of flat
140 surfaces characterized by topographic culminations with elevation ranging through a few
141 meters around a mean value. Selected topographic culminations of the reconstructed paleo-

142 surfaces were detected on ~~the~~Istituto Geografico Militare 1:25.000 topographic maps of Italy
143 ~~edited by Istituto Geografico Militare~~. They include all the hilltops (i.e., each elevation point
144 within a closed, 5 m ~~space~~interval contour line, represented by upward triangles in the
145 figures of this work) and other quasi-equivalent points within plateau-like sectors
146 (downward triangles). The identification of the paleo-surfaces ~~implies is based on~~ a combined
147 approach that integrates statistically significant concentrations of elevations around a mean
148 value, and the morphologic evidence for the concentration of these elevation points within a
149 finite area, as detected in the maps (see Marra et al., 2016a for detailed methodology). The full
150 dataset of topographic elevations is reported on the scanned 1:25.000 topographic maps and
151 provided as Supplementary Material #1 ~~to this work~~.
152 Distribution of the topographic culminations has been statistically analyzed in order to verify
153 the occurrence of discrete elevation intervals corresponding to peaks of concentration, which
154 can be assumed ~~as to be~~ the mean ~~value~~level for each paleo-surface. Comparison between
155 the complete dataset of elevation points (hilltops + plateaux) and that represented only by
156 hilltop elevations has been also provided, to highlight possible subjective selection of the
157 plateau-like culminations and to exclude biases.
158 Finally, a set of elevation ranges defining the principal paleo-surfaces identified ~~through using~~
159 the described geomorphological method has been ~~elaborated mapped through by~~ DEM
160 analyses, to compare the results.

162 **3.2 DEM analysis**

163 Five classes of elevations highlighted by the geomorphological study have been mapped using
164 an interferometric Digital Elevation Model (DEM) with a ground resolution of 30 meters (1
165 arcsec) derived from the NASA SRTM mission (<http://www2.jpl.nasa.gov/srtm>, Farr et al.,
166 2000). ~~In detail~~When the overall topographic relief of the Italian peninsula is considered, the
167 DEM shows an averaged altitude accuracy of ~15 meters, but in our case, considering areas
168 quite close to the sea and showing low altitude ~~values~~ranges (i.e., 0 - 120 m), the accuracy is
169 ~~most likely~~one order of magnitude better, and can be estimated in 1-2 m.
170 The analysis was ~~totally~~ performed ~~entirely within into~~ a GIS environment. Initially, the DEM
171 was ~~cut~~delimited on the basis of the study area using a polygon shapefile, then the various
172 classes were identified one by one, generating 5 different layers. ~~To this aim, 5~~Five queries
173 were applied to the DEM, each time considering the maximum and minimum values of each
174 class so ~~as to~~ only isolate the desired altitude interval. Finally, the layers were merged into a
175 single one and symbolized with 5 different colors, one for each class.

176

177 3.3 Micromorphological analyses

178 Three undisturbed soil samples (TML-CC, VDT, VOC) and three loose sand samples (TML-SA,
179 PC-SA, CSR-SA) have been studied in thin sections for micromorphological analysis and for
180 sand mineralogy determination, respectively, aimed at investigating the pedological and/or
181 sedimentological features, and to recognize the origin of the deposit forming the
182 corresponding paleo-surface. One sediment sample collected ~~in from~~ the paleo-surface
183 ranging 60-67 m (CR1) in the northern sector was analyzed ~~for a work~~ by Villa et al. (2018),
184 and the results are reported here to integrate ~~with~~ the dataset above.

185 Descriptions of thin sections are summarized in Table 1, results of the petrographic
186 determination of sand grains are reported in Table 2. Methods and microphotographs of thin
187 sections for micromorphological analyses are provided in Supplementary File #2A.

188

189 3.4 Mineralogical analyses

190 Fifteen ~~soil~~ samples collected close to the top, and in some instances at increasing depth, on
191 the different paleo-surfaces (VL-1, VL-2, MM, VCR-1, VCR-2, VCR-3, TB-1, TB-2, TB-3, VVL,
192 TML-SA, TRIG, VDT, SPR, RUT), and three sediment samples (RSC, CDC, CR-1), have been
193 analyzed by X-rays diffraction and ~~at the scansion~~ ~~with a scanning~~ electron microprobe (SEM)
194 in order to describe their mineralogy and texture.

195 Methods, microphotographs and full-resolution diffractograms are provided in
196 Supplementary File #2B-C.

197

198 3.5 ~~⁴⁰Ar/³⁹Ar dating~~

199 Sanidine crystals ~~have been were~~ extracted from four samples of sediment to provide
200 terminus post-quem ages to the time of deposition of the terrains and/or the accretionary
201 soils forming the paleo-surfaces ranging 98-108 m (TML-SA), 71-79 m (RSC-SA), 60-67 m
202 (CR-3), 51-57 m (CSR-SA) a.s.l., in the area ~~comprised~~ between the Tiber mouth and Anzio.
203 Sampling locations ~~is provided~~ ~~are shown~~ in Figure 3.

204 Sanidine phenocrysts were co-irradiated with the 1.1864 Ma Alder Creek sanidine standard
205 (Jicha et al., 2016; Rivera et al., 2013) at the Oregon State University TRIGA reactor in the
206 Cadmium-Lined In-Core Irradiation Tube. Single crystal fusion analyses were performed at
207 the WiscAr laboratory at the University of Wisconsin-Madison using a 60W CO₂ laser and a
208 Noblesse multi-collector mass spectrometer following Jicha et al. (2016). Results are reported
209 in Table 4. Full analytical data are reported in Supplementary Material #3.

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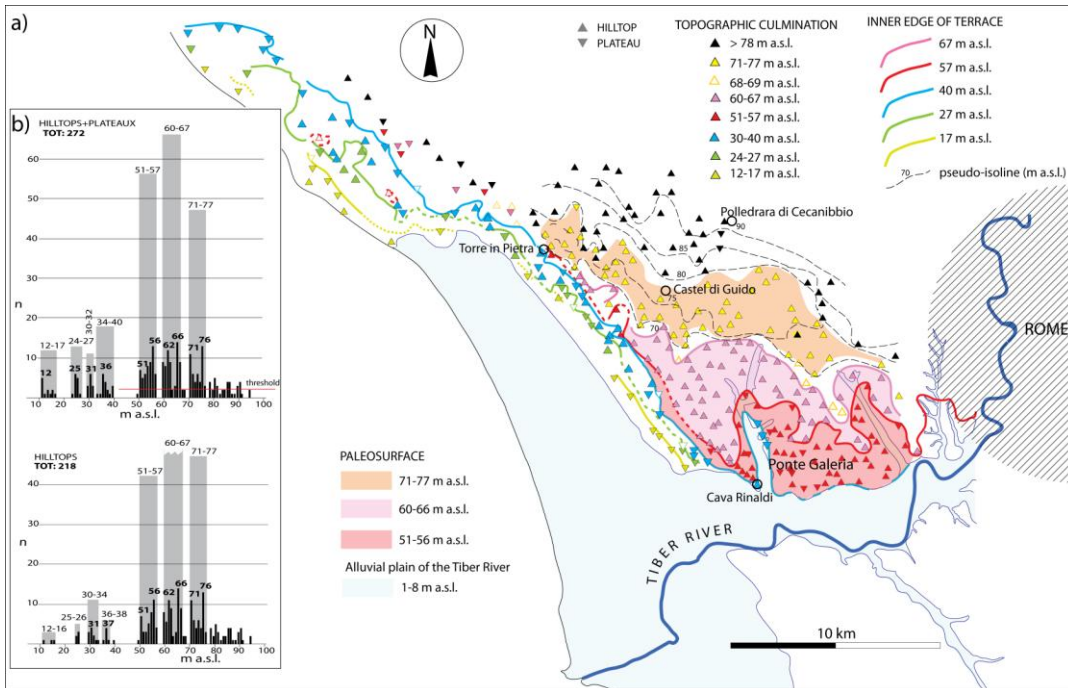
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210

211 4. Results

212 4.1 Geomorphological analysis

213 Results of the geomorphological study performed for the present work in the coastal area
214 between Civitavecchia and Anzio are in good agreement with those previously obtained by
215 Marra et al. (2016a, 2019a). We have statistically re-analyzed hilltops and plateaux elevations
216 separately, in the two coastal sectors north and south of the Tiber mouth. Very similar
217 statistical assessment for the elevation ranges of the detected paleo-surfaces have been
218 obtained for the two sectors, which are reported in Figure 2 and 3, respectively. In these
219 figures, all the topographic culminations identified ~~in-on~~ the 1:25.000 maps are ~~reported~~
220 ~~indicated~~ with triangles of different colors. In the northern sector, each color is associated
221 with an elevation range defining a paleo-surface which, in turn, is established ~~based-on~~~~from~~
222 the statistical analysis. Elevation ranges for the paleo-surfaces are represented by grey boxes
223 of ~~cumulated-cumulative~~ frequency above a threshold value of $n=2$ for a total number of data
224 >20 (red horizontal line in Figure 2b), while continuous distributions are considered for
225 classes of $n < 20$. Open triangles are used for hilltops whose elevation is not statistically
226 significant and are not associated with a paleo-surface. These elevations are interpreted ~~to-as~~
227 reflect~~ing~~ topographic culminations ~~that~~ represent~~ing~~ eroded higher rank paleo-surfaces; for
228 this reason, the same color used for the corresponding pristine paleo-surface is ~~also~~ used ~~also~~
229 for these triangles.

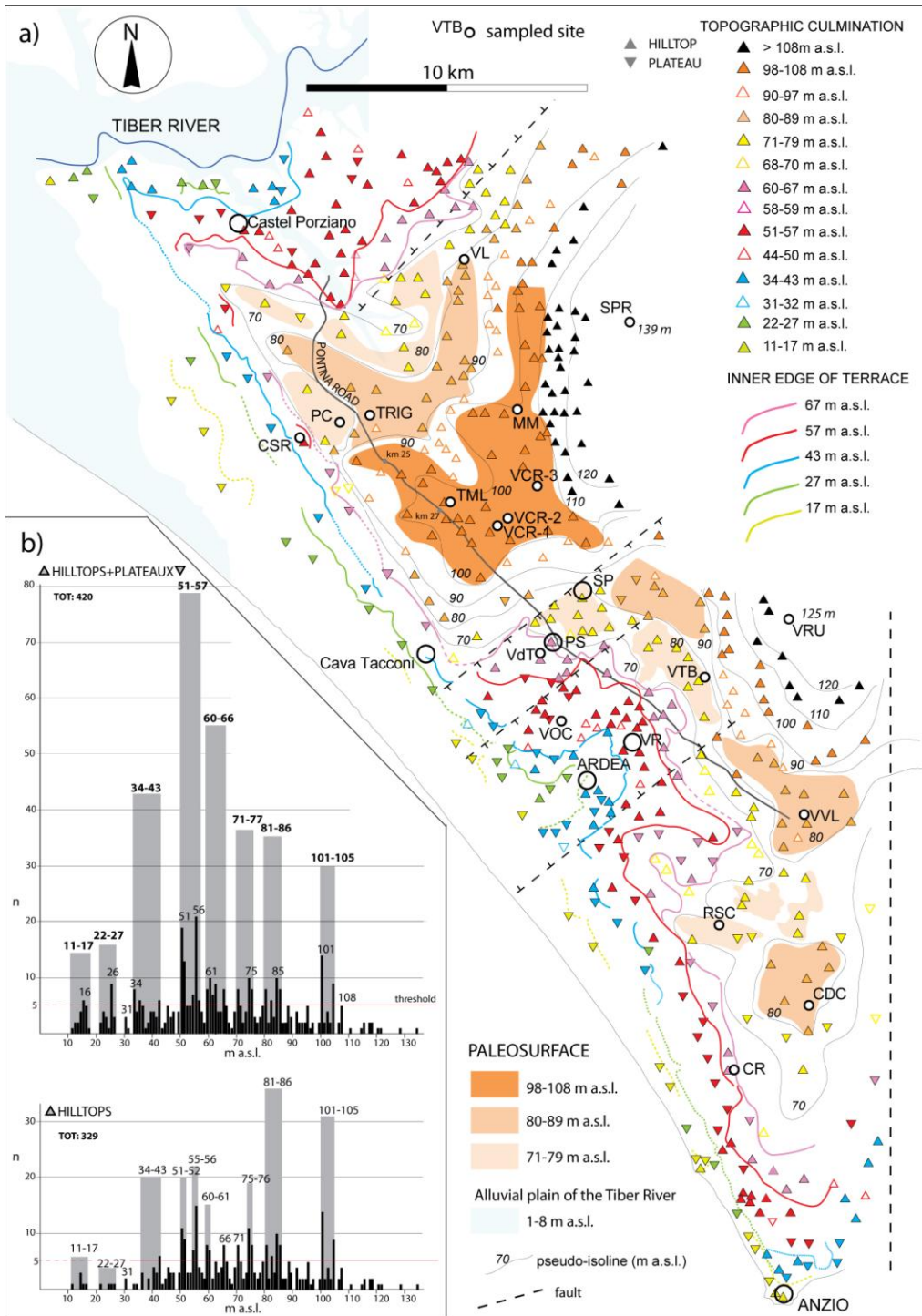


230

231 Figure 2 - Geomorphological map (a) and ~~statistics of~~ topographic culmination ~~statistics~~ (b) in
 232 the northern sector ~~comprised~~ between Civitavecchia and the Tiber mouth. Elevations of
 233 topographic culmination are omitted for clarity in this figure and can be found in Suppl. Mat.
 234 #1A. See text for comments.

235

236



237
 238 Figure 3 - Geomorphological map (a) and ~~statistics of~~ topographic culmination ~~statistics~~ (b)
 239 in the southern sector ~~comprised~~ between the Tiber mouth and ~~the~~ Anzio promontory.
 240 Elevations of topographic culmination are omitted for clarity in this figure and can be found in
 241 Suppl. Mat. #3. See text for comments.

242

243 A similar approach is used in the southern sector where, due to the larger number of data, a
244 threshold value of n=5 is established to define the classes of elevation for all the paleo-
245 surfaces ~~but except~~ the lowest two (Figure 3b). Moreover, in a few cases ~~the~~ elevation range
246 for each color is slightly larger than the mean elevation range (grey boxes) established for the
247 paleo-surfaces based on histograms, in order to include all topographic points.

248 Color shading is used in Figure 2 for three oldest paleo-surfaces which have ~~more a wider~~
249 ~~extension extent~~ and are located inland, while inner margins are represented by solid colored
250 lines for the paleo-surfaces stretching along the coast, which are assumed to represent coastal
251 terraces. Different shades of the orange color are used in Figure 3 to highlight the highest
252 paleo-surfaces that are located inland which, according to discussion in the following sections,
253 are interpreted as having the same age, whereas inner ~~terrace margins of terrace~~ are reported
254 for the youngest paleo-surfaces along the coast.

255 In both sectors illustrated in Figures 2 and 3, three lowest orders of terrace are identified by a
256 series of topographic culminations, each one providing well-clustered, distinct elevation
257 ranges, which define three paleo-surfaces narrowly elongated parallel to the coast. The lowest
258 paleo-surface ranges 12-17 m a.s.l., with a peak at 12 m (Figure 2b), and 12-18 m a.s.l., with a
259 peak at 16 m (Figure 3b), in the northern and in the southern sector, respectively. A second
260 paleo-surface has very narrow ranges of 24-27 and 22-27 m a.s.l., with peaks at 25 and 26 m,
261 in the northern and in the southern sector, respectively.

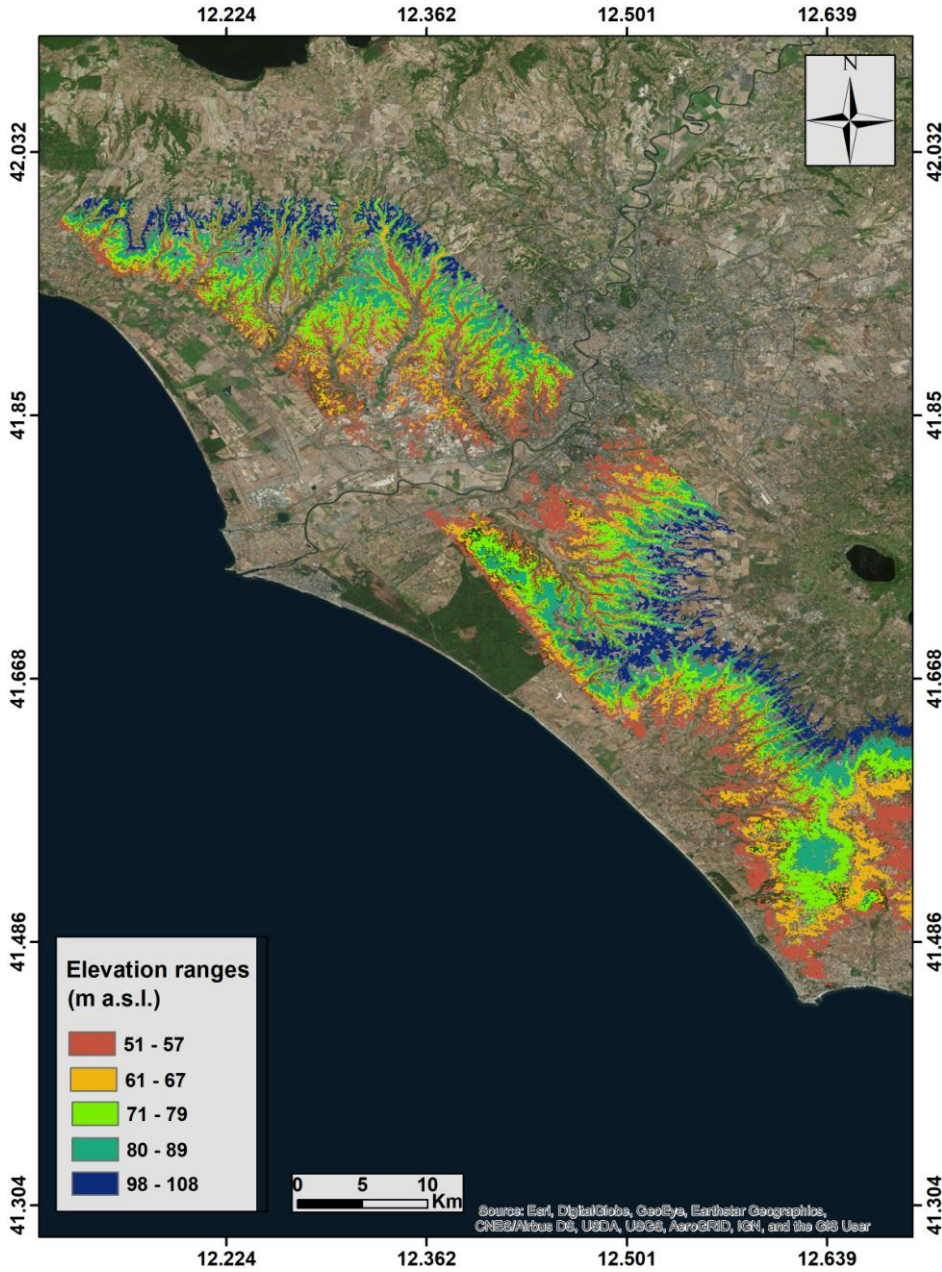
262 A third, higher paleo-surface is characterized by a wider range of elevations, with a main
263 concentrations between 34-40 and 34-43 m a.s.l. in the northern and southern sector,
264 respectively, and with a minor peak at 31 m, in both sectors.

265 A fourth, wide paleo-surface is that ranging 51-57 m a.s.l. and characterized by two relative
266 maxima at 51 and 56 m, in both sectors. Another two well-defined elevation ranges of 60-67
267 m, and of 71-77 m, are clearly identified in both sectors, and ~~are~~ associated with ~~a fifth and a~~
268 sixth paleo-surfaces, respectively.

269 Finally, two more concentrations of elevation values, ~~peaked peaking~~ at 80-86 and 101-105 m
270 a.s.l., define the two highest paleo-surfaces ~~in on~~ the inland coastal sector south of the Tiber
271 mouth, whereas in the northern sector topographic culminations show progressively
272 increasing elevation inland, without any apparent clustering around a mean value.

273 Comparison of the results of the geomorphological study with the DEM of Figure 4 shows a
274 very satisfactory match. In particular, we ~~remark note~~ the close correspondence between the
275 geometrical patterns defined by the 51-57 m paleo-surface in the geomorphological maps of

276 Figure 2 and 3, and in the DEM image of Figure 4 (represented by the red color in both
277 representations), as well as, between those pertaining to the highest paleo-surface of 98-108
278 m (represented by the deep orange color in Figure 3 and by the deep blue color in Figure 4).



279
280 Figure 4 - Interferometric Digital Elevation Model (DEM) mapping of the five classes of
281 elevations highlighted by the geomorphological study.
282

283

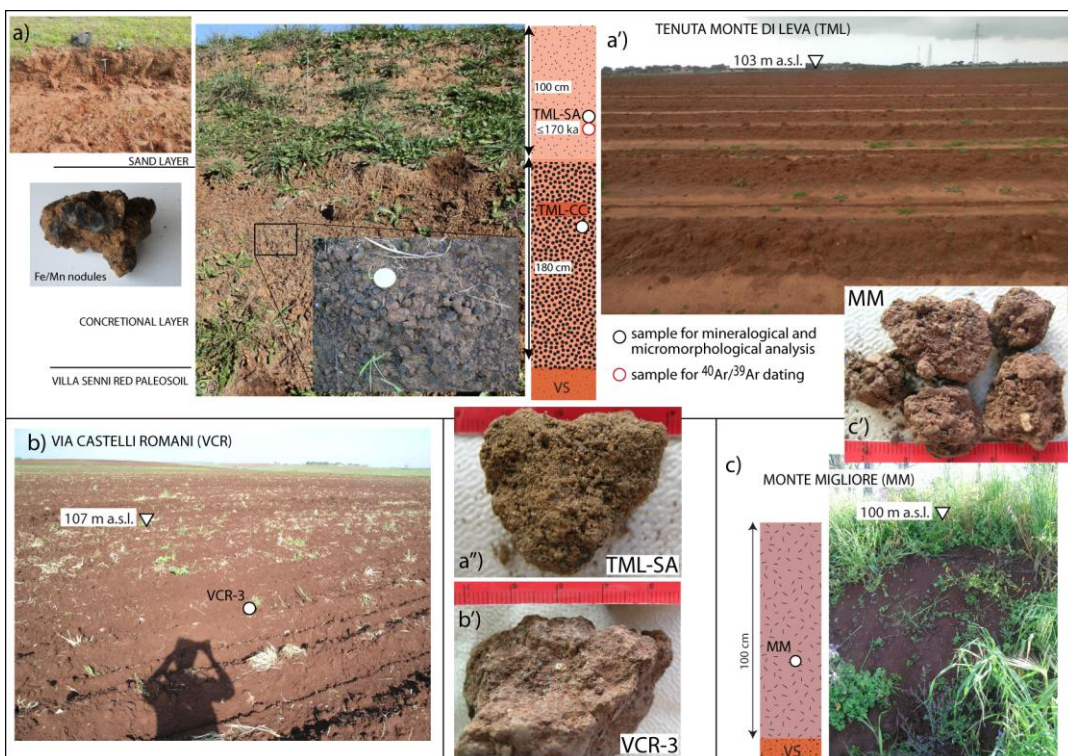
284

285 4.2 Stratigraphic investigations

286 4.2.1 Paleo-surface 98-108 m a.s.l.

287 Exposure of the sedimentary deposits forming the highest paleo-surface in the investigated
288 area is provided by a road cut in Tenuta Monti di Leva (TML), at km 27 of Via Pontina (Figure
289 5a, see Figure 3 for location). Here, an **upper pedogenically modified horizon** occurs
290 **layer** occurs in the upper 100 cm and is constituted by fine to medium sized sand in silty-
291 clayey matrix, orange in color (Figure 5a-a"). A 180 cm thick **concretionary** layer,
292 constituted by aggregated, cm-sized Fe and Mn nodules within a sand matrix, occurs at the
293 bottom of this **layer-horizon** and overlies a red paleosol developed on top of the pyroclastic-
294 flow deposit of Pozzolanelle (Villa Senni Eruption Cycle, 365±4 ka; Freda et al., 1997; Marra et
295 al., 2009). A sample of the upper sand layer (TML-SA) and **another one sample off from** the
296 **concretionary** layer (TML-CC) **have been were** analyzed for mineralogy and
297 micromorphology, respectively. Forty-one sanidine crystals extracted from sample TML-SA
298 **have been were** dated by **the** $^{40}\text{Ar}/^{39}\text{Ar}$ method.

298



299

300 Figure 5 - Photographs and stratigraphic schemes showing the 98-108 m a.s.l. paleo-surface
301 and the sections from which samples analyzed in the present study were collected. See text
302 for comments.

302

303

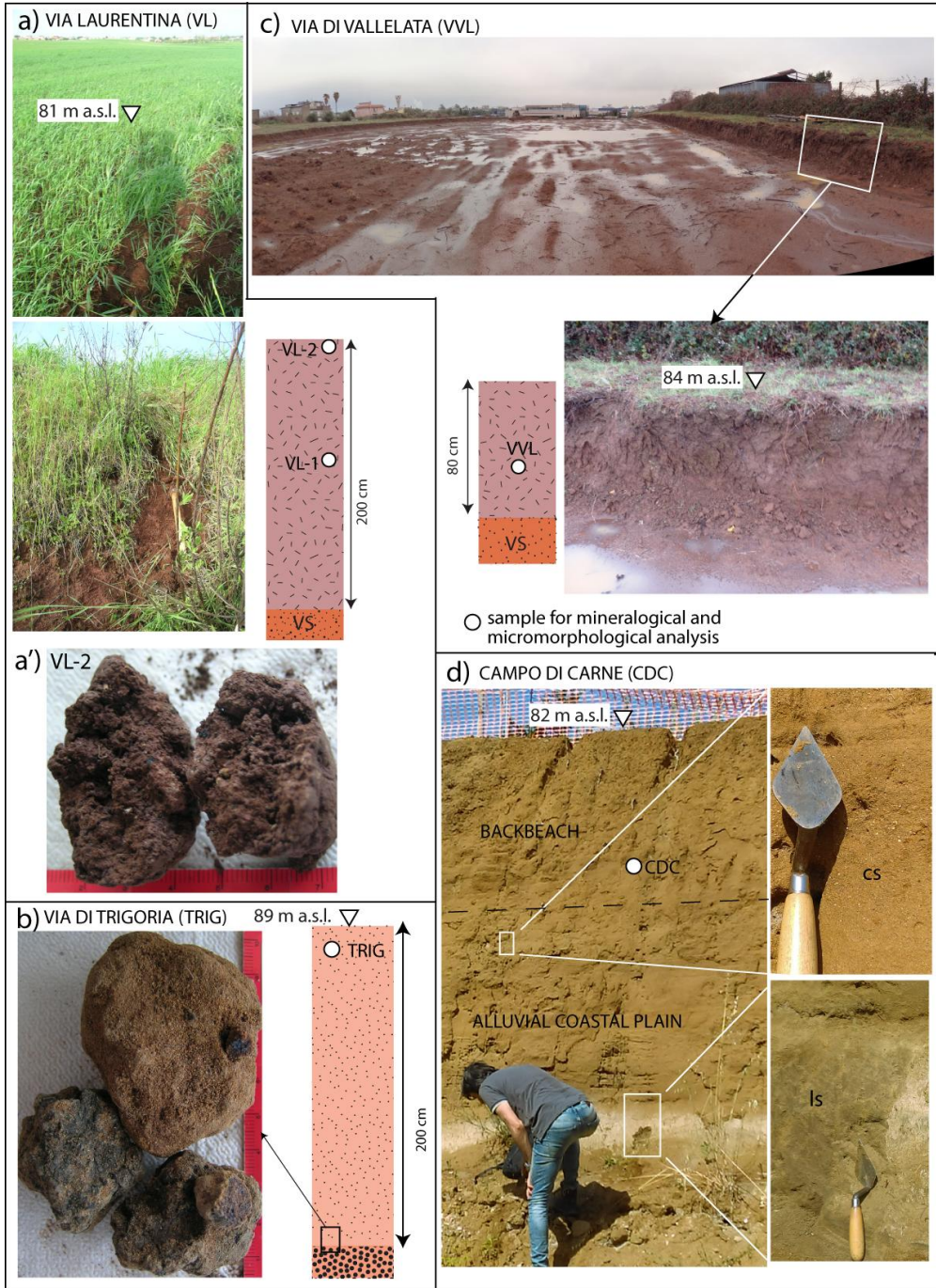
304 | The Tenuta Monte di Leva paleo-surface is affected by intensive ~~plowing-ploughing~~ which
305 | exposes shreds of the upper, orange sand layer, allowing ~~to recognize~~recognition of the
306 | presence of this sedimentary deposit throughout the sector crossed by the Pontina Road
307 | between km 27 and km 25 (see Figure 3a). A similar in color, but finer sandy-clay deposit is
308 | exposed by plowing grooves on top of this highest paleo-surface, ~~more~~further inland. Four
309 | samples were collected along ~~the~~ Via dei Castelli Romani and Via Laurentina, at increasing
310 | distance inland, with respect to the Tenuta Monte di Leva site (Figure 3). Three samples (VCR
311 | 1-3) were collected at elevations ~~s comprised~~ between 105 and 107 m a.s.l. in the ~~plowed~~
312 | exposing clods of the sub-~~surface portion of the~~ soil (Figure 5b). Although the direct contact is
313 | not exposed in this flat sector, a geologic substrate represented by the Pozzolanelle
314 | pyroclastic-flow deposit (hereby PL) is visible in the scanty outcrops along the stream
315 | incisions at its margin. A fourth sample (MM) was collected ~~in-at the~~ Monte Migliore-La
316 | Selvotta locality, at 100 m a.s.l., from the middle of a 100 cm thick, dark red ~~paleosol~~paleosol
317 | developed above the PL, exposed by a road cut (Figure 4c). A larger amount of clay matrix,
318 | dark red in color, characterizes the samples collected in these inland sectors of the 98-108
319 | paleo-surface (VCR 1, 2, 3, MM, Figure 5b'-c'). Frequent pyroxene crystals and sparse, altered
320 | volcanic scoriae 1 to 5 mm in size, are embedded in the clay matrix of these soils, evidencing
321 | an at least partial origin from the directly underlying volcanic deposit.
322 | Two more samples were collected in a later time at higher elevation, in the area inland with
323 | respect to that pertaining to the 98-108 paleosurface (SPR at 139 m a.s.l.) and with respect to
324 | the narrow alignment of topographic culminations ranging 100-110 m in the more southern
325 | sector (RUT at 125 m a.s.l.) (Figure 3), aimed at investigating the origin of the abundant silico-
326 | clastic fraction highlighted by micromorphologic and petrographic analyses in the soils
327 | developed above the volcanic substrate.

328

329 | **4.2.2 Paleo-surface 80-89 m a.s.l.**

330 | Different ~~shreds~~fragments of this paleo-surface are identified northwest and southeast of the
331 | highest sector corresponding to the 98-108 paleo-surface (Figure 3). As ~~occurring~~
332 | latter, ~~also~~ the 80-89 paleo-surface ~~is also develops~~developed above different geologic
333 | substrates as a function of the distance from the coastline: above the PL in the inland sectors,
334 | and above sedimentary sand deposits to the southwest. Five samples were collected in the
335 | different sectors of this paleo-surface. Two samples (VL-1, VL-2, Figure 6a) were collected in
336 | the middle and at the surface of a thick ~~paleosol~~paleosol developed above the PL in Via

337 | Laurentina, in the inland margin of the northernmost stretch of this paleo-surface. ~~One more~~
 338 | **further** sample (TRIG, Figure 6b) was collected at its opposite, seaward extreme, on the
 339 | ground surface in a sandy deposit (Figure 3).



340

341 Figure 6 - Photographs and stratigraphic schemes showing the 80-89 m a.s.l. paleo-surface
342 and the sections from which samples analyzed in the present study were collected. See text
343 for comments.

344 This sedimentary deposit is quite similar to that cropping out in Tenuta Monte di Leva (TML):
345 ~~it's-it is~~ a ~~medium-medium-to-to-~~ fine ~~sized~~grained, orange sand in ~~a scarce-sparse~~ clay matrix,
346 without sedimentary structures, ca. 3 m thick (Figure 6b). At the base of the exposed section a
347 ~~concretionalconcretionary~~ layer rich in Mn/Fe nodules, quite similar to that occurring in TML,
348 is present.

349 A fourth sample (VVL, Figure 6c) was collected in the middle of an ca. 80 cm thick
350 ~~paleosoilpaleosol~~ developed above the PL in Via Vallelata, in the inland margin of the
351 southernmost stretch of the 80-89 m paleo-surface (Figure 3). This reddish soil, like the
352 thicker soil sampled in Via Laurentina (Figure 6a'), ~~is~~ constituted ~~by~~s of very fine, clayey
353 sediment ~~conglobating-containing~~ abundant pyroxene crystals and altered volcanic scoriae,
354 and appears quite similar to the other soils developed directly above the PL sampled for this
355 study.

356 Finally, one sample (CDC) was collected in Campo di Carne in a road excavation exposing an
357 ca. 3 m thick ~~sedimentary~~ deposit constituted ~~by~~ing of fine, faintly bedded sand in ~~scarce-a~~
358 ~~sparse~~ clay matrix, with dm-thick layers of coarse sand (cs in Figure 6d), whose top at 82 m
359 a.s.l. is part of the seaward portion of the 80-89 m a.s.l. paleo-surface. A layer of dark, greenish
360 loamy fine sand, ca, 60 cm thick, occurs at the base of the exposed section in CDC (ls in Figure
361 6d).

362

363 4.2.3 Paleo-surface 71-79 m a.s.l.

364 Two particularly level, small sectors at elevations around 76 m a.s.l. ~~are-can be~~ detected in the
365 northern and southern margins of the investigated area, in ~~the~~ Podere Carafa (PC) and
366 Riserva Carpineto (RSC) estates (Figure 3). In ~~the~~ PC, an almost perfectly flat area (Figure 7a)
367 is truncated by a sharp scarp to the southwest, dividing it from another level area at ca. 56 m
368 a.s.l. (Castel Romano -CSR), while it ~~more-gently~~ connects ~~more-gently~~ to a slightly higher
369 sector, corresponding to the 80-89 paleo-surface, to the northeast. A marked fluvial incision
370 dissecting the plateau exposes the terrains forming the 71-79 m paleo-surface, showing ~~an-at~~
371 ~~least five meters thick,~~ massive sand deposit ~~of at least five meters thickness,~~ where sample
372 PC-SA analyzed ~~in this work~~during this study was collected (Figure 7a).

373 A remarkably similar geomorphologic and stratigraphic setting is observed ~~in-at the~~ RSC. Here
374 a wide level area at elevations ranging 70-79 m is intensely dissected by steep stream valleys,
375

376 and almost without geomorphologic break connects with another large area to the southeast,
 377 including the Campo di Carne (CDC) site, at an elevation ~~comprised~~ between 80 and 85 m a.s.l.
 378 ~~to the southeast~~ (Figure 3). A massive, medium to coarse sand deposit with sparse, well-
 379 rounded fine gravel (sample RSC, Figure 7b) constitutes the geologic substrate in this area,
 380 and directly overlies the lower flow unit of the Villa Senni eruption cycle (Tufo Lionato).



381

382 Figure 7 - Photographs and stratigraphic schemes showing the 71-79 m a.s.l. paleo-surface
383 and the sections from which samples analyzed in the present study were collected. See text
384 for comments.
385

386 A portion of this 71-79 m a.s.l. paleo-surface also occurs within the structurally controlled
387 sector of Ardea, bordered by the NE-SW trending normal faults of the Ardea Basin (Figure 3).
388 This is a half-graben which originated as a transversal Tyrrhenian Sea basin in Lower
389 Pleistocene times, as evidenced by off-shore seismic lines (Faccenna et al., 1994). The
390 continued Middle Pleistocene activity of these faults is suggested by the marked control on
391 the paleo-coastlines, testified by the geometry of the inner edges of the MIS 7 and MIS 5
392 terraces reconstructed in Marra et al. (2016a, 2019a) and shown by our refined study in
393 Figure 3 and in Figure 4.

394 ~~Differently than in~~In contrast to the more seaward sectors, here the 71-79 paleo-surface is
395 developed upon the PL (Figure 7c-d), and characterized by a shallow, 60-80 cm thick, dark
396 brown ~~paleosol~~paleosol. Three samples have been vertically sampled in this
397 ~~paleosol~~paleosol in at the Via di Torre Bruna (VTB 1-3, Figure 7c).

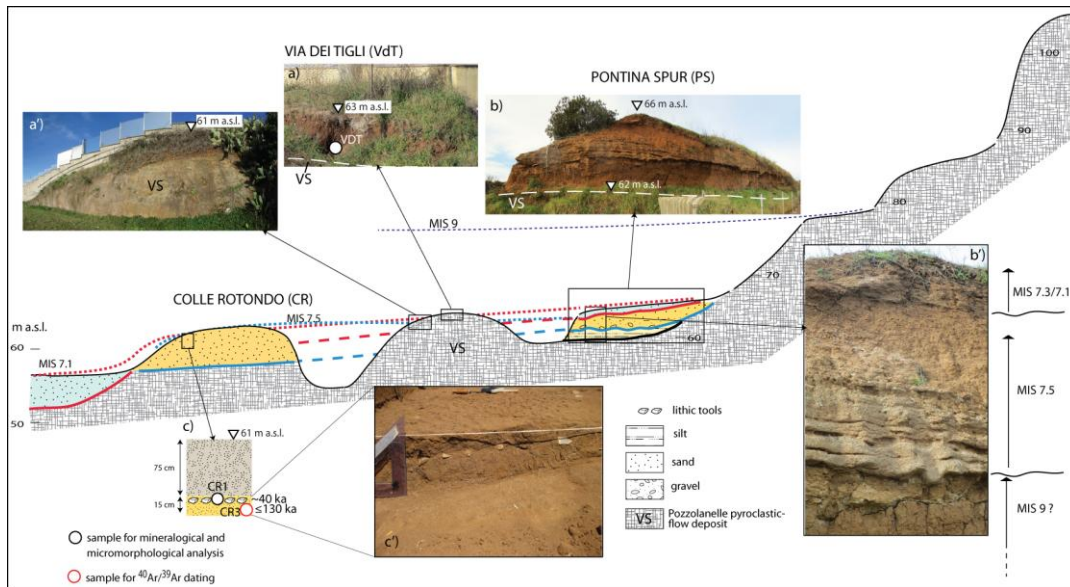
398 Figure 2 shows a wide 71-77 m paleo-surface that we have reconstructed in the coastal sector
399 north of the Tiber mouth (Ponte Galeria area), which in Marra et al. (2016a) was not
400 highlighted. However, scanty sedimentary deposits occur at these elevations in this area,
401 where the outcropping terrains are mostly represented by the Monti Sabatini volcanic
402 succession. Notably, thin layers of calcareous lacustrine muds, ca. 50 m thick, ~~crop~~s out at
403 ~~elevation of~~ 72 m a.s.l. in Castel di Guido, and are overlain by the pyroclastic-flow deposit of
404 Tufo Giallo di Sacrofano (285±2 ka, Karner et al., 2001b; Sottili et al., 2010), which forms most
405 of the hilltops of the 71-77 m paleo-surface (Marra et al., 2018c). We interpret these
406 sedimentary strata as the remnants of an alluvial coastal plain, mantled by a thin cover of
407 pyroclastic deposits.

408

409 **4.2.4 Paleo-surface 61-67 m a.s.l.**

410 No evident paleo-surface is associated with this class of elevations in the sector south of the
411 Tiber mouth, except that pertaining to small, isolated plateaux, like ~~in at the~~in at the Colle Rotondo
412 locality (CR, Figure 8). The Colle Rotondo site is located on the flat surface of an E-W
413 elongated hill, culminating 63.5 m a.s.l., bordered by the steep flanks of two convergent
414 streams, 2.5 km east of the present coast, and 7.5 km north of Anzio (Figure 3). This is part of
415 a series of hilltops ranging 61-67 m a.s.l., aligned along a narrow stripe of land defining a
416 coastal terrace between Ardea and Anzio (pink triangles in Figure 3). This terrace is shifted

417 inland, significantly, within the Ardea basin, paralleling the behavior of the inner edge of the
 418 51-57 m terrace, as well as that of the two lower terraces of 34-43 m, and 22-27 m (Figure 3).
 419 Notably, in the coastal sector overlooking the most elevated area of TML, corresponding to the
 420 98-108 m paleo-surface, only plateau points define the 60-67 m terrace, while almost no
 421 evidence of the 51-57 m terrace occurs in the coastal reach north of the Ardea basin,
 422 consistent with erosion due to tectonic uplift of this sector. In contrast, a well-defined 60-67
 423 m terrace occurs at the northwestern margin of the lower area represented in Figure 3, facing
 424 the terminal reach of the Tiber Valley.



425
 426 Figure 8 - Composite cross-section, constructed by projecting the Colle Rotondo (CR) site on
 427 an ideal profile passing by the Santa Procula (SP), Pontina Spur (PS), and Via dei Tigli (VdT)
 428 sites (see Figure 3 for location), aimed at showing the stratigraphic relationships between the
 429 sedimentary successions underlying the 60-67 m a.s.l. paleo-surface.

431 A pedogenized surface horizon constituted by of brown sandy silt, heavily disturbed by
 432 plowing/ploughing, occurs in the upper 75 cm at CR (Figure 8c). It overlies a reddish-brown
 433 silty sand horizon, incorporating mm-sized Mn and/or Fe concretions (Figure 8c'). A large
 434 number of stone artifacts attributed to the Uluzzian culture (45-41 ka) was found within the
 435 upper portion of this sand layer, ranging in thickness from 6 to a maximum of 20 cm (Villa et
 436 al., 2018). One sand sample (CR1) collected within the archaeological layer was analyzed for
 437 micromorphology by Villa et al. (2016), while 39 sanidine crystals extracted from a sand
 438 sample (CR3) collected immediately below (see Figure 8c) have been dated as part of
 439 the present work.

440 A different geologic substrate characterizes the 60-67 m paleo-surface at two sites located in
441 the northern portion of the Ardea Basin, Via dei Tigli (VdT) and Pontina Spur (PS) (Figure 3).
442 A ca. 80 cm thick, brown-reddish clayey ~~paleosol~~paleosol overlies overlies the PL ~~in at~~
443 (Figure 8a). Field surveys ~~in this area~~ showed that the substrate of the 60-67 m paleo-surface
444 in this area is ~~systematically constitute~~represented by a pedogenized layer on top of the PL (e.g.,
445 Figure 8a'). One sample ~~of from~~ this soil (VdT) has been analyzed for micromorphology.
446 A peculiar situation is observed at PS, where two fining-upwards successions overlie a third,
447 faintly bedded fine sand deposit, which in turn overlies the PL (Figure 8b-b'). The two upper
448 successions ~~are constituted by~~consist of a basal gravel layer, made up of reworked ~~volcanics~~
449 volcanic material with ~~idiosyncratic~~characteristic, large, ~~analcimized~~ leucite crystals turned
450 into analcime, suggesting provenance from the PL (Freda et al., 1997). The finer, upper part is
451 also prevalently made up largely of volcanic sand. Both have evident fluvial origin. The lowest
452 layer is a silty fine sand, of possible palustrine or alluvial origin. No sample was collected from
453 this section, due to its very local significance, while a correlation with the other sections of the
454 60-67 m paleo-surface and a paleoenvironmental interpretation is provided in the cross-
455 section of Figure 8.

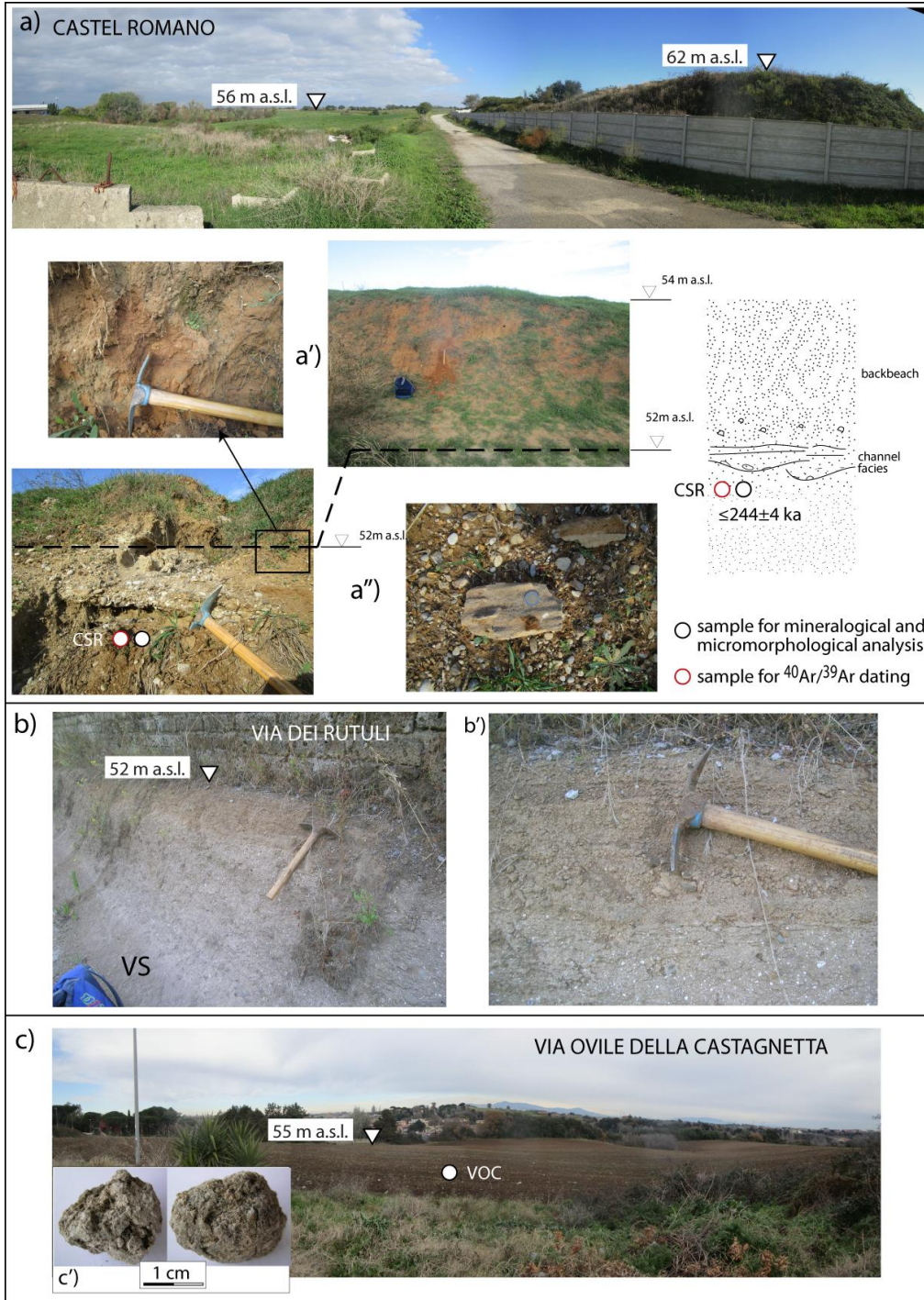
456 The 60-67 m paleo-surface has a wide expression to the north of the Tiber ~~River~~ (Figure 2).
457 However, no sedimentary succession is apparently associated with this paleo-surface, ~~where~~
458 its geologic substrate ~~is constituted by~~consisting of different, older volcanic deposits, ranging
459 561-400 ka (e.g., Karner and Marra, 1998; Marra et al., 2016b), which form the hilltops in this
460 area. Consequently, the 60-67 paleo-surface in this area should be considered as a non-
461 depositional terrace, possibly generated by uplift-induced erosional processes in the near-
462 shore sector, similar to the overlying higher level paleo-surface of 71-77 m in this sector.

463

464 **4.2.5 Paleo-surface 51-57 m a.s.l.**

465 This paleo-surface (red triangles in Figure 2 and 3) has a prominent expression in the Ponte
466 Galeria area north of the Tiber mouth, where solid geochronologic constraints correlate it
467 with MIS 7, as ~~remarked~~noted in Marra et al. (2016a). It is rather well preserved along the
468 southeastern side of the Tiber Valley, south of the River-river mouth, and in the southernmost
469 sector between Ardea and Anzio, while it disappears along the coastal reach facing the TML
470 morpho-structural height (Figure 3). However, two shreds-fragments of coastal terrace are
471 preserved immediately north of this sector, and one of these (Castel Romano -CSR) provides
472 good exposure of the terrains underlying the paleo-surface. ~~In At~~ CSR a large level area at
473 elevations ranging 51-56 m a.s.l. is bordered to the west-northwest by a steep, 6 m ~~tall~~high

474 scarp (Figure 9a), separating it from the other wide level area of Podere Carafa, ranging 71-79
 475 m a.s.l. (see Figure 3).
 476



477

478 Figure 9 - Photographs and stratigraphic schemes showing the 51-57m a.s.l. paleo-surface and
479 the sections from which samples analyzed in the present study were collected. See text for
480 comments.

481
482 The 60-67 m terrace is not preserved between the two paleo-surfaces in this area, which are
483 connected by a gentle incline degrading from ca. 70 m to 62 m a.s.l., behind the sub-vertical
484 scarp. The 51-56 m paleo-surface ~~in at~~ CSR is dissected by a gully exposing on its banks a
485 reddened, massive sand deposit, 2 m thick (Figure 9a'), overlying a ca. 50 cm thick layer with
486 gravel lenses and sandstone horizons with ripple marks (Figure 9a"). This braided channel
487 facies overlies a massive sand deposit in which sample CSR for mineralogical analysis and
488 $^{40}\text{Ar}/^{39}\text{Ar}$ dating was collected.

489 A different geologic substrate represented by the PL characterizes the 51-57 m paleo-surface
490 within the Ardea Basin. However, exposure ~~in at~~ Via dei Rutuli (VR, see Figure 3) provides
491 evidence of a conglomeratic layer above the PL at 52 m a.s.l. (Figure 9b), which testifies the
492 occurrence of a transgressive deposit that should be considered the coastal deposit associated
493 with the 51-57 terrace in this area. It is a bedded, fining upward, 50 cm thick sand and gravel
494 layer, ~~englobating containing~~ well-rounded scoria clasts from the underlying pyroclastic
495 deposit, which is erosionally truncated at the top (Figure 9b'). Evidence from another site
496 within the Ardea basin (Via Ovile della Castagnetta -VOC, Figure 3) suggests that a fine-
497 grained, lagoon deposit forms the upper portion of the 51-57 terrace in this area. Here, a wide
498 paleo-surface around 55 m a.s.l. (Figure 9c) ~~is constituted by~~ consists of a brown, mature
499 ~~paleosol~~ paleosol in which one sample (VOC) was collected and analyzed for
500 micromorphology. The occurrence of abundant, rounded calcareous concretions (Figure 9c'),
501 which are uncommon in shallow soils developed directly upon the siliceous volcanic deposits,
502 suggests the presence of a horizon of calcareous mud, as typically observed in the lagoon
503 deposits of the MIS 7 Vitinia Formation (Karner and Marra, 1998) associated with the 51-57
504 paleo-surface in the northern coastal sector.

505

506 **4.3 Micromorphological analyses**

507 Results of thin section observations are summarized in Table 1.

508

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TS ¹	Microstructure	Lithology	Groundmass ²	c/f ratio	Rel Dist ³	Pedofeatures
TML-CC	-	Matrix: 15 -20% fine sands (quartz; rare feldspar; chert; metamorphic rock fragments) Inside nodules: well sorted fine sands (±45%) (quartz; feldspar; chert; metamorphic rock fragments; pyroxene)	Orange (PPL) clay with SS and GS bfabric	20/80 (matrix) 50/50 (nodules)	OP (matr.) SSP (nod.)	Matrix: layered clay coatings and infillings, limpid and silty clay, broad extinction lines, frequent.
CR1	Basic MS type: close porphyric	Fine sand (5%); Medium sand (60-65%) Lithology: quartz; feldspar; chert; pyroxene; metamorphic rock fragments; epidote. Sub-rounded and sub-angular grains.	Reddish (PPL) clays with SS and GS b-fabric	70/30	CP	Limpid clay coatings and infillings, 1st order yellow interference colors; broad extinction lines, occasional superimposed Fe coatings.
VDT	Subangular blocky, moderate	Very fine sand (5-10%); Fine sand (5%); Medium sand (5-10%) Lithology: quartz; chert; pyroxene (rare); Sub-rounded and sub-angular grains.	Orange (PPL) clay with CS and GS bfabric	20/80	OP	Limpid clay coatings, strongly deformed, frequent. Disorthic Fe/Mn nodules, typical and concentric, frequent, rounded.
VOC	Basic MS type: single-spaced porphyric	Very fine sand (±5%); Fine sand (15-20%); Medium sand (25-30%) Lithology: quartz; feldspar; chert; pyroxene; amphibole; volcanic scoria (rare); metamorphic rock fragments. Sub-rounded and sub-angular grains.	Yellowish (PPL) clays with GS bfabric	60/40	SSP	Limpid clay coatings, strongly deformed, frequent. Disorthic Fe/Mn nodules, typical and concentric, frequent, rounded.

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Table 1 – Description of thin sections

¹ TS = Thin Section

² B-fabric: SS = Stipple speckled; PS = porostriated; GS = granostriated; CS = cross striated

³ Rel Dist = Related distribution pattern: CP = close porphyric; SSP = single-spaced porphyric; OP = open porphyric

519

520 **4.3.1 ~~Concretion~~Concretionary layer from Tenuta Monte di Leva: sample TML-CC**

521 Micromorphological analysis ~~on of~~ this sample collected ~~in from~~ the TML

522 ~~concretion~~concretionary layer shows that the nodules are iron and manganese concretions

523 that entrap sediments differing from those in the surrounding groundmass. The main

524 differences between the sediments within the nodules and those in the matrix around them

525 are as follows:

526 (a) The degree of sorting, which inside the nodules is good, with grains in the fine sand class,

527 indicating that the nodules formed in aeolian or alluvial sands (e.g., channel facies).

528 | (b) The lithology: the matrix ~~has-consists~~ only of weathering resistant species, whereas in the
529 | nodules some volcanic minerals (pyroxenes – Fig. S1) are ~~still~~-preserved, and feldspar (e.g.,
530 | microcline) is more abundant than in the surrounding matrix.
531 | The matrix around the nodules shows the effects of marked pedogenesis. It is in fact very clay-
532 | rich and in the coarse fraction only weathering resistant ~~species-are~~material is preserved
533 | (quartz, chert, metamorphic rock fragments – predominantly quartzite). Clay coatings,
534 | pertaining to several superimposed episodes of clay illuviation, are very strongly ~~attested~~
535 | developed (Fig. S2). They occur as superimposed limpid and silty clay coatings or as coatings
536 | deformed due to shrink-swell phenomena.
537 | ~~Excluding-Albeit~~ that the nodules may be allochthonous (i.e., formed elsewhere and then
538 | transported and re-deposited after being eroded), observations attest that they contain
539 | remains of the former parent material on which pedogenesis ~~took~~has taken place,
540 | “preserving” it from successive weathering. Weathering and pedogenesis subsequently
541 | affected ~~then~~ the groundmass but were ~~hampered~~impeded within the nodules.
542 |

543 | **4.3.2 Sand deposit from Colle Rotondo: sample CR-1**

544 | The sand fraction is composed of a mixture of ~~silicoelastic~~siliciclastic and volcanoclastic (i.e.
545 | pyroxenes – augite) mineral species. The moderate sorting, the grain size centered on the
546 | medium sand granulometric class, and the slight rounding of the grains are compatible with
547 | an aeolian (backbeach) sediment. There are no traces of reworking due to surface runoff or
548 | similar water and gravity-triggered slope processes. Pedogenesis is at an initial stage,
549 | especially compared to other samples from this study. Incipient reorganization of the
550 | groundmass, giving rise to a stipple-speckled b-fabric, is observed. Weak traces of incipient
551 | clay illuviation, such as thin clay coatings around skeletal grains, also point to an
552 | initial/moderate level of pedogenesis (Fig. S3). The weatherable minerals in the coarse
553 | fraction – especially pyroxenes – are abundant and do not show traces of weathering.
554 |

555 | **4.3.3 ~~Paleosol~~Paleosol from Via dei Tigli: sample VDT**

556 | This sample shows the highest degree of pedogenic weathering ~~in~~amongst the analyzed
557 | sample ~~lots~~. The abundant clay in the groundmass shows orange-red colors resulting from the
558 | strong oxidation, and the clay ~~themselves~~ are the outcome of repeated cycles of clay
559 | illuviation. Strong vertic processes (i.e.: internal turnover of soil material) led to the digestion
560 | of the illuvial clays in the fine mass and to the formation of strongly developed cross-striated
561 | and grano-striated b-fabric types (Fig. S4, S5). Also the nodules of iron and manganese owe

562 their morphology to the strong shrink-swell phenomena in the sample (which led to the
563 formation of concentric nodules with strong rounding). The coarse fraction is predominantly
564 composed of weathering-resistant species (quartz and chert), albeit minor amounts of
565 pyroxenes and unaltered volcanic glass are still present. The latter might derive from a
566 'fresher' or more recent input of volcanoclastic material into the soil during its formation. The
567 poor sorting, sub-angular morphology and medium-fine sand grain size of the **silicoelastic**
568 **siliciclastic** fraction do not **match the expected characteristics of account for** an aeolian input,
569 strongly suggesting an alluvial/colluvial origin.

570

571 **4.3.4 Paleosol/Paleosol from Via Ovale della Castagnetta: sample VOC**

572 The sorting of the coarse fraction is low. The sample has the highest percentage of volcanic
573 mineral grains (pyroxenes and amphiboles – see Fig. S6) in the studied set, included the loose
574 sand samples. The fine fraction derives from clay illuviation, which ultimately triggered vertic
575 processes and the digestion of clay coatings within the groundmass, the development of a
576 grano-striated b-fabric, and the formation of concentric iron and manganese nodules.
577 Grains are predominantly in the fine and medium sand fraction, and show subrounded and
578 rounded morphologies. The low sorting and the rounding of iron and manganese nodules
579 indicate reworking and redeposition of the material. The presence of rare calcite infillings
580 indicates re-carbonation of the profile due to the effect of a dissolved carbonate-rich
581 groundwater table (Fig. S6). Abundant, large (1-2 cm) carbonatic nodules also occur in the
582 deposit.

583

584 **4.4 Mineralogical analyses in thin section**

585 **4.4.1 sample TML-SA**

586 Due to the granulometric bias introduced by sieving, it is not possible to ascertain the
587 sedimentary environment in which the deposit formed through thin section observation.
588 Nevertheless, it can be said that TML-SA is characterized by **scaree-scanty** medium and coarse
589 sand fraction, and by fine material possibly indicating pedogenesis. Indeed, the fine material
590 was observed before the sieving and also after it, especially in the form of "pseudosands"
591 which survived the sieving procedure. The nature of the sand grains is essentially **silicoelastic**
592 **siliciclastic** (Table 2), with a very minor volcanoclastic fraction and lack of volcanic scoriae.
593 Grains have a subangular morphology.

594

595

Minerals	TML - SA	PC-SA	CSRM-SA
	%	%	%
Quartz	64	66	35
Metamorphic rock fragments	20	19	35
Chert	12	10	16
Feldspar	3	2	5
Pyroxene	1	3	8
Amphibole	1	0	0
Volcanic scoria	0	0	1
Total siliciclastic %	98	97	91
Total volcanoclastic %	2	3	9
Counted grains (n)	152	156	154

596
597
598

Table 2: results of petrographic determination of sands

599 Quartz, chert, metamorphic rock fragments (mainly quartzite with minor amounts of schist)
600 and feldspar have been grouped under the “~~siliciclastic~~ siliciclastic” category. Pyroxene (mostly
601 augite and monocline pyroxene, diallagio), amphiboles (green and brown hornblende) and
602 volcanic scoria belong to the “volcanoclastic” category.

603

604 4.4.2 Sand deposit ~~from at~~ Podere Carafa: sample PC-SA

605 The sand displays strikingly similar grain composition (Table 1) and morphology as that of
606 sample TML-SA.

607

608 4.4.3 Sand deposit ~~from at~~ Castel Romano: sample CSR-SA

609 This sand sample is characterized by medium grain size with a subrounded morphology and
610 no fine matrix. Mineralogical composition displays a higher percentage of volcanic species
611 ~~with respectin to comparison with~~ the other sand samples (Table 1).

612

613 4.5 X-ray and SEM analysis

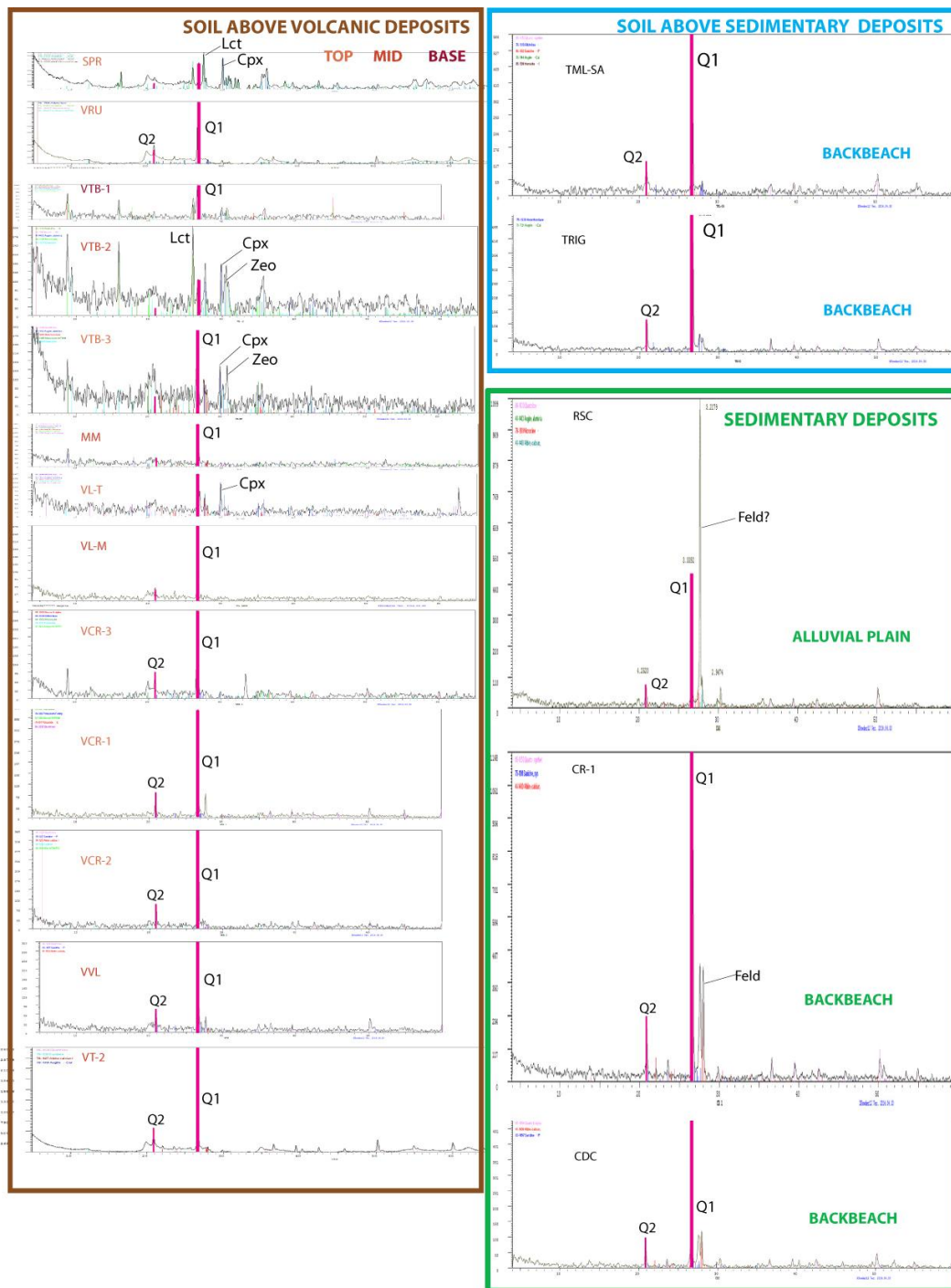
614 Results of diffractometric analyses are summarized in the diagrams of Figure 10.

615 Calcic clinopyroxene is ubiquitous in the pyroclastic rocks of the Colli Albani volcanic district.

616 In addition, amorphous material ~~deriving derived~~ from the weathering of volcanic glasses is
617 typical of soils developed on pyroclastic rocks (generally, this soil component is identified in
618 the RDX by the increase of counts in the region at lower 2θ). Consequently, the height of
619 clinopyroxene peak at $2\theta=29.85^\circ$, as well as that of amorphous material at $2\theta=4^\circ$, with
620 respect to quartz peak at $2\theta=26.65^\circ$ in the RDX can be assumed as an indicator of the
621 abundance of volcanic components forming the soil. This provides an index (i.e.

622 $Qtz/(AM+Cpx)$ in Table 3) to distinguish the soils developed above a primary volcanic
623 substrate (Index <6) from those overlying sedimentary deposits (Index >6).

624 Notably, quartz is present in all the soils developed above volcanic deposit and its abundance
625 generally increases with decreasing depth as evidenced by magnitude of the peak at
626 $2\Theta=26.65^\circ$ (Q1 Figure 10a). Quartz is practically absent closer to the base of the soil in VTB-1,
627 and is scarce in the middle of the soil in VTB-2 and in Monte Migliore (MM). However, it is also
628 abundant in the middle of VVL and VL, where the Q1 peak is comparable with that of all the
629 surface samples. A marked quartz peak is present in sample VdT-2, from the soil developed
630 above the Villa Senni deposit on the 61-67 terrace, for which the ~~silicoclastic~~siliciclastic
631 fraction has been investigated in thin section for micromorphology on sample VdT-1.
632 However, excluding the sample VCR-1, notably the closest one to the inferred
633 sedimentary/volcanic transition in Figure 11, all the soils developed above volcanic deposit
634 show higher amount of AM+Cpx (>12) in comparison with ~~respect~~ the others soils analyzed
635 in this study (Table 3).



636

637 Figure 10 - Diffractograms of the soil and sediment samples. In inset a' diffractograms are...
 638 Vertical axes are normalized to the same scale; full-resolution original diagrams are provided
 639 in Suppl. Mat. #1B. See text for comments.

640

641 Moreover, quartz abundance decreases with the distance from the inferred paleo-shoreline in
642 soils developed above the volcanic substrate. In order to verify this observation, we have
643 collected two samples in the inland sector at the foot of the Colli Albani peri-calderig-caldera
644 ring (SPR and RUT, Figure 11) and we have normalized results of diffractometric analyses
645 performed with a different equipment (see Methods in Supplementary Material #2) by re-
646 analyzing samples VTB-1 and VTB-3 with them (Table 3). As shown in Figure 10 and Tabkle 3,
647 Q1 peaks and AM+Cpx/Qz are the highest one for thesec samples.
648 Apart for the discriminating AM+Cpx/Qz ratio, diffractograms of soils above sedimentary
649 deposits differ from those above volcanic deposits only for the slightly larger magnitude of the
650 main quartz peak Q1, and for the presence of a second quartz peak close to 10 (Q2). These
651 peaks are much higher in the sediment samples which also display a remarkable peak
652 corresponding to the pyroxene. Finally, the smaller magnitude of the quartz and pyroxene
653 peaks in the fine sediment sample CDC suggests that magnitudes are also proportional to
654 grainsize of the siliceolastic component.
655 Abundance, dimension and morphology of the Quartz and K-feldspar grains occurring in
656 selected samples (VTB-1, TML-SA, VCR-1, CR1) have been analyzed at the SEM and discussed
657 in section 5.1. Microphotographs are provided in Supplementaerty Material #2.
658

	SOILS ABOVE VOLCANIC DEPOSITS															SOILS ABOVE SEDIMENTARY DEPOSITS				
	VTB-1	VTB-2	VTB-1	VV	VL-M	VL-T	MM	VTB-1*	VTB-3*	VRU*	SPR*	VdT-2*	VCR-3	VCR-2	VCR-1	TRIG	TML-SA	RSC	CDC	CR-1
Amorphous	305	240	8000	58	54	121	45	68	9900	6100	8500	4750	80	70	30	52	59	55	45	110
Qtz	290	122	8000	320	270	147	150	0	20700	15977	6650	26343	316	349	394	520	586	1099	501	1168
Cpx	165	165	11500	0	10	118	15	40	9300	750	8000	550	25	0	10	20	20	40	20	0
TOT	760	527	27500	378	334	386	210	108	39900	22827	23150	31643	421	419	434	592	665	1194	566	1278
Amorphous	40	46	29	15	16	31	21	63	25	27	37	15	19	17	7	9	9	5	8	9
Qtz	38	23	29	85	81	38	71	0	52	70	29	83	75	83	91	88	88	92	89	91
Cpx	22	31	42	0	3	31	7	37	23	3	35	2	6	0	2	3	3	3	4	0
TOT	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Qtz/Cpx+AM	0,6	0,3	0,4	5,5	4,2	0,6	2,5	0,0	1,1	2,3	0,4	5,0	3,0	5,0	9,9	7,2	7,4	11,6	7,7	10,6
Cpx+AM	62	77	71	15	19	62	29	100	48	30	71	17	25	17	9	12	12	8	11	9

659
660 Table 3 - X-ray powder diffraction (XRPD) data. Summary of absolute abundances of
661 mineral phases in the analyzed samples (*samples analyzed with a different
662 equipment, see Methods in Supplementary Material #2).

663

CR3	
Age (ka)	$\pm 2\sigma$ (ka)
127,7	$\pm 11,3$
130,9	$\pm 11,2$
131,0	$\pm 9,6$
131,7	$\pm 9,7$
133,4	$\pm 13,7$
134,0	$\pm 14,3$
138,3	$\pm 6,3$
140,6	$\pm 12,5$
169,5	$\pm 6,9$
169,7	$\pm 11,7$
177,6	$\pm 8,3$
198,4	$\pm 7,3$
245,3	$\pm 6,6$
249,9	$\pm 7,2$
250,7	$\pm 6,5$
251,6	$\pm 6,6$
298,9	$\pm 5,6$
375,6	$\pm 4,9$
379,1	$\pm 5,6$
392,9	$\pm 9,6$
393,5	$\pm 4,8$
400,2	$\pm 4,6$
401,4	$\pm 5,1$
403,6	$\pm 4,7$
407,3	$\pm 5,6$
407,8	$\pm 4,6$
410,7	$\pm 6,5$
416,5	$\pm 3,5$
418,1	$\pm 4,6$
421,7	$\pm 3,8$
446,8	$\pm 4,6$
459,2	$\pm 5,1$
495,5	$\pm 6,5$
498,4	$\pm 4,8$
503,2	$\pm 4,1$
1289,3	$\pm 6,5$
1289,9	$\pm 3,9$
1293,0	$\pm 6,9$
1313,1	$\pm 3,5$
youngest population:	
134,2	$\pm 3,5$
249,3	$\pm 3,4$

664

665

TML-SA	
Age (ka)	$\pm 2\sigma$ (ka)
151,1	$\pm 27,6$
165,5	$\pm 28,5$
166,6	$\pm 27,9$
171,0	$\pm 24,9$
181,7	$\pm 25,4$
189,3	$\pm 54,3$
216,5	$\pm 6,0$
239,9	$\pm 4,7$
246,2	$\pm 17,8$
250,0	$\pm 6,6$
252,3	$\pm 7,1$
257,6	$\pm 5,1$
262,8	$\pm 22,7$
266,0	$\pm 20,0$
287,5	$\pm 72,5$
316,8	$\pm 18,7$
329,8	$\pm 20,8$
335,5	$\pm 96,7$
351,5	$\pm 15,7$
361,0	$\pm 40,6$
368,2	$\pm 32,7$
369,5	$\pm 20,0$
371,2	$\pm 21,5$
372,6	$\pm 18,7$
382,2	$\pm 23,2$
389,6	$\pm 23,0$
398,9	$\pm 16,2$
409,6	$\pm 5,9$
422,9	$\pm 63,3$
430,5	$\pm 10,9$
435,7	$\pm 8,7$
446,4	$\pm 5,6$
504,4	$\pm 5,6$
541,7	$\pm 5,0$
549,4	$\pm 5,4$
551,8	$\pm 4,3$
557,0	$\pm 40,2$
589,3	$\pm 4,4$
600,0	$\pm 6,4$
1328,9	$\pm 8,0$
1339,3	$\pm 15,9$
youngest population:	
169	± 11

666

667

CSR-SA	
Age (ka)	$\pm 2\sigma$ (ka)
232,3	$\pm 19,8$
240,9	$\pm 8,2$
244,5	$\pm 5,7$
246,8	$\pm 6,9$
263,1	$\pm 4,6$
263,7	$\pm 29,1$
310,1	$\pm 16,3$
395,5	$\pm 5,0$
407,9	$\pm 4,4$
476,6	$\pm 7,1$
488,3	$\pm 5,3$
494,5	$\pm 4,7$
500,8	$\pm 6,8$
508,5	$\pm 3,5$
542,1	$\pm 17,2$
552,1	$\pm 9,0$
563,1	$\pm 6,2$
597,3	$\pm 3,7$
625,7	$\pm 6,7$
805,2	$\pm 9,7$
youngest population:	
244,0	$\pm 3,8$

668

CAR-SA	
Age (ka)	$\pm 1\sigma$ (ka)
298,19	$\pm 3,50$
397,35	$\pm 2,69$
397,55	$\pm 2,50$
401,16	$\pm 3,23$
401,50	$\pm 6,70$
401,92	$\pm 4,30$
409,08	$\pm 4,09$
409,45	$\pm 2,28$
410,43	$\pm 3,01$
416,80	$\pm 2,14$
417,80	$\pm 1,90$
417,86	$\pm 27,38$
420,18	$\pm 3,26$
430,43	$\pm 2,92$
447,50	$\pm 15,16$
461,11	$\pm 3,89$
468,78	$\pm 18,49$
523,49	$\pm 3,21$
566,40	$\pm 2,82$
580,99	$\pm 3,19$

669

670

671

672 Table 4 - $^{40}\text{Ar}/^{39}\text{Ar}$ ages of dated samples

673

674

675 **4.6 $^{40}\text{Ar}/^{39}\text{Ar}$ data**

676 Single crystal age data for the three analyzed samples are reported in Table 4. Full analytical
677 data are provided in Supplementary Material #3.

678 **4.6.1 Sample CR3**

679 Thirty-nine sanidine crystals extracted from the sand sample collected ca. 90 cm below the
680 ground surface in Colle Rotondo provided a wide age spectrum, ranging 1.31 through 0.13 Ma.
681 A youngest population of eight crystals yielded a weighted mean age of 134 ± 3.5 ka.

682 **4.6.2 Sample TML-SA**

683 Forty-one sanidine crystals extracted from the sand sample collected ca. 60 cm below the
684 ground surface in Tenuta Monte di Leva provided ages ranging 1.34 through 0.15 Ma. A
685 youngest population of six crystals yielded a weighted mean age of 169 ± 11 ka.

686 **4.6.3 Sample CSR-SA**

687 Twenty sanidine crystals extracted from the sample collected in the fluvial sand cropping out
688 in Castel Romano provided ages ranging 0.80 through 0.23 Ma. A youngest population of four
689 crystals yielded a weighted mean age of 244 ± 4 ka.

690 **4.6.4 Sample RSC-SA**

691 Twenty sanidine crystals extracted from the sample collected in the fluvial sand cropping out
692 in Riserva Carpineto provided one isolated, youngest crystal of 298 ± 3.5 ka. The majority of
693 the crystal ages are spread in the interval 398-468 ka, with three oldest crystals ranging 523 -
694 581 ka.

695

696 **5. Discussion**

697 **5.1 Soils and paleo-surfaces**

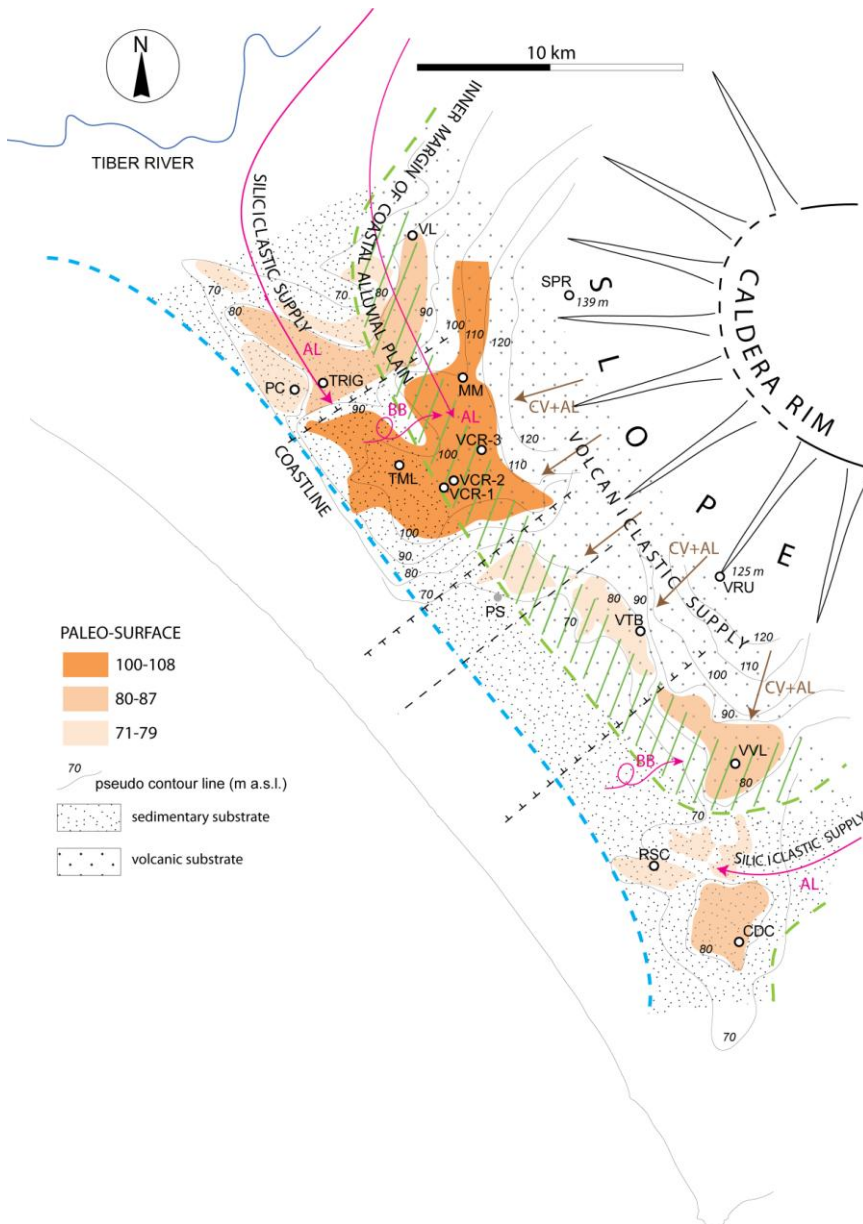
698 Analysis of soil samples for the present study has been conducted aimed at identifying their
699 sedimentologic and petrographic features, in order to understand their origin and the
700 paleogeographic conditions in which they formed. Pedologic considerations and a complete
701 study of the processes ~~that superintended to~~involved the formation of these soils, as well as
702 laboratory granulometric analyses are beyond the scope of the present work. Our main scope
703 is to verify ~~at which to what~~ extent the present ground surfaces characterized by the same
704 elevations range represented in Figure 2 and 3 can be considered indicative of the original
705 paleo-surfaces representing the ancient coastal settings. In particular, we want to quantify the
706 possible amount of later deposition, or erosion, which may have increased or decreased,
707 respectively, the average elevation of these paleo-surfaces, therefore affecting our estimation
708 of the sea-level related with the corresponding coastal terrace.

709 When studying the composition of the soils developed above the reconstructed paleo-
710 surfaces, some preliminary considerations are necessary. In particular, when the paleo-
711 surfaces of highest order are considered (i.e. those ranging 98-108, 80-89, and 71-79 m a.s.l.,
712 Figure 3), we must realize that the sub-horizontal attitude of these isolated, plateau-like
713 sectors ~~prevents-precludes~~ alluvial sedimentation, almost completely. ~~In second~~
714 ~~instance~~ Furthermore, the whole catchment area drained by these paleo-surfaces ~~is develops~~
715 ~~developed~~ above volcanic deposits. Therefore, the ~~siliceoelasticiliclastic~~ component of the
716 soils above the paleo-surfaces of this sector, which in the X-ray diagrams is sometimes
717 predominant, can only have the following two origins:

- 718 i. it can be a back-beach to coastal plain sediment originally deposited above the volcanic
719 substrate when the paleogeographic conditions allowed ~~it~~ (i.e.: before the regional uplift,
720 when the paleo-surface represented a coastal environmental setting) (BB and AL in Figure
721 11a);
- 722 ii. it can be an aeolian sediment (i.e., loess-like) accumulated above the volcanic deposits
723 through air-fall emplacement and successively diffused within the soil by vertic processes
724 (i.e.: internal turnover of soil material originated by pedogenetic processes).

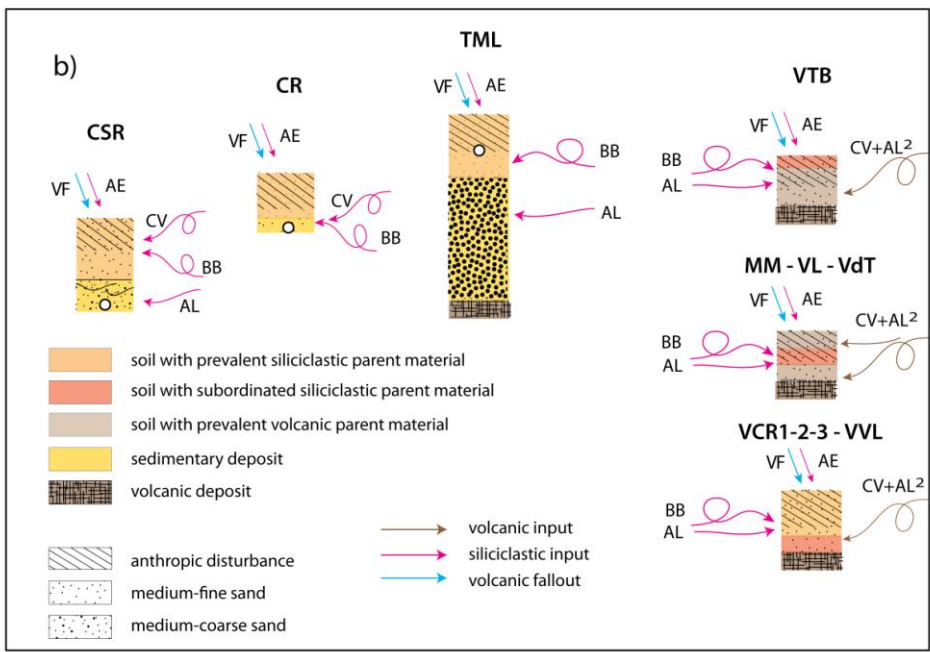
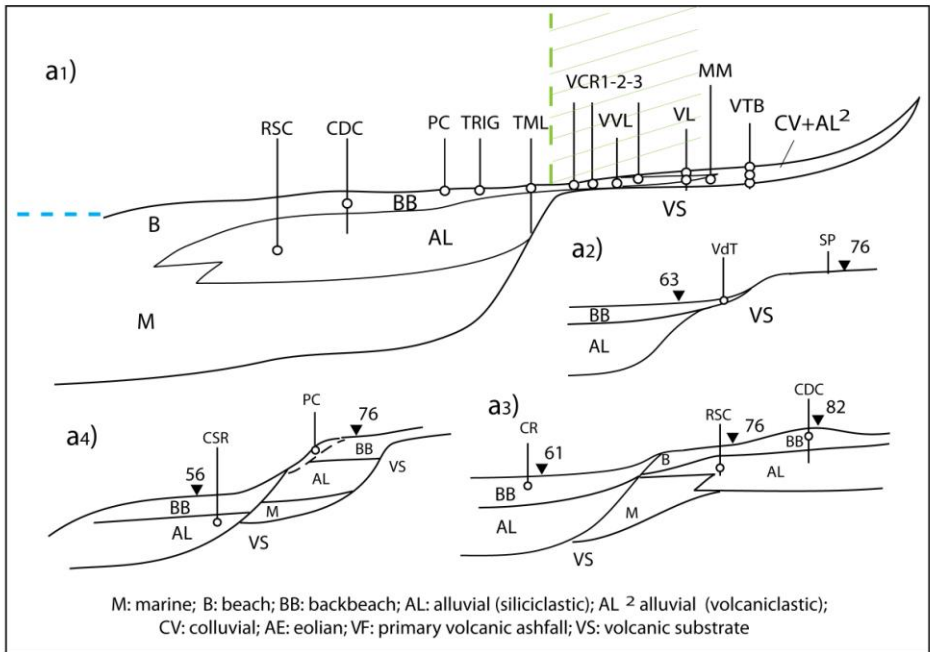
725 Recognizing the origin of this ~~siliceoelasticiliclastic~~ sediment is therefore fundamental in
726 order to reconstruct the paleogeographic setting of these paleo-surfaces, correctly, as shown
727 in Figure 11, ~~where-in which~~ the paleogeographic scenario is illustrated. The dashed green
728 line in Figure 11 separates the sampling sites where field observation have shown that the
729 present soil overlies sedimentary sand deposits (to the southwest), from those where the soil
730 ~~is develops-developed~~ above the volcanic deposit of Pozzolanelle (to the northeast), as
731 reported also in the cross-section of Figure 12. The oblique green lines indicate the area
732 where the ~~siliceoelasticiliclastic~~ fraction in the analyzed soils ~~is-is~~ predominant.
733 Composition of the analyzed soils overlying the volcanic deposit of Pozzolanelle, with
734 abundant quartz and feldspar, combined with micromorphological and SEM analyses which
735 confirm the sedimentary origin ~~for-of~~ the quartz grains but rule out an aeolian (loess-like)
736 origin, at least for the larger fraction (>200 μm ; Figure S7), demonstrate that these soils affect
737 thin (≤ 1 m) layers of alluvial and backbeach, ~~prevalently-predominantly~~ ~~siliceoelasticiliclastic~~
738 deposits. ~~Consistent to~~ ~~In keeping with~~ this interpretation, quartz abundance strongly
739 decreases in soil samples collected ~~in~~ more inland ~~locations~~ (SPR, RUT), far from the inferred
740 paleo-coastline (Figure 10).

741
742



744

745 Figure 11- Paleogeographic reconstruction of the MIS 9 coastal setting. Stratigraphic
 746 investigations and sedimentologic-, micromorphologic, mineralogic and petrographic
 747 analyses on sediment and soil samples have allowed at recognizing to detect a transitional
 748 zone (oblique green dashes) in correspondence of ing with the inner margin of the coastal
 749 plain, where a thin horizon of backbeach to alluvial deposits overlaps the volcanic substrate.
 750 (see also cross-section in Figure 12a). This reconstruction evidences the occurrence of an
 751 original, homogeneous paleo-surface, subsequently disrupted and dislocated by tectonic
 752 movements, which originated-gave rise to three main flat sectors at elevations ranging 100-
 753 108, 80-87, and 71-79 m a.s.l. (see text for comments).



754

755 Figure 12 - a1-4) Cross-sections restored from tectonic dislocation showing the original
 756 paleogeographic and sedimentary settings reconstructed in the area where the soil and
 757 sediment samples were collected. b) Origin of the different sedimentary inputs contributing to
 758 the formation of the deposits and the related soils at the top of the paleo-surfaces
 759 reconstructed in the present study. See text for comments.

760

761 Alluvial/colluvial volcanic material (CV+AL in Figure 112b and 12), ~~deriving~~ derived from the
762 rocks cropping out at the inner margin of the coastal alluvial plain (green dashed area in
763 Figure 11), were also continuously mixing with the alluvial and backbeach, ~~prevalently~~
764 ~~predominantly silicoelastic~~ ~~iliclastic~~ deposits transported by the Tiber River and deposited
765 in the coastal plain. Moreover, air-fallen material including either loess-like sediment (AE in
766 Figure 12b), ~~as well~~ as primary air-fallen volcanic ash (VF in Figure 12b), also progressively
767 accumulated above this soils and ~~were~~ ~~was~~ diffused by vertic processes ~~into~~ the sub-surface
768 horizon. To this aeolian fraction must be ascribed part of the K-feldspar observed in this
769 section and evidenced in the diffractograms, as well as part of the finest silico-clastic
770 component.

771 Such ~~an~~ air-fall contribution must be extended to the soils developed above the sedimentary
772 deposits, in which the volcanic component is also represented by re-deposited mineral
773 species of the underlying sedimentary substrate, incorporated in the soil through colluviation,
774 surface water and wind transport (CV in Figure 12b).

775 These mechanisms are ~~resumed~~ ~~envisaged~~ in Figure 12, showing the different
776 paleogeographic and sedimentary settings reconstructed in the area where the soil and
777 sediment samples were collected. The age spectra provided by sanidine crystals extracted
778 from the lowest portion (unaffected by agricultural disturbance) of the backbeach deposits
779 above which the soils of the 98-108 and of the 61-67 paleo-surfaces ~~have~~ developed (TML-SA,
780 CR3; Figure 13), compared to that of the "sealed" sedimentary deposit of the fluvial facies
781 (RSC-SA, CSR-SA), provide further insights to the processes described above.

782

783 **5.2 Age of the paleo-surfaces**

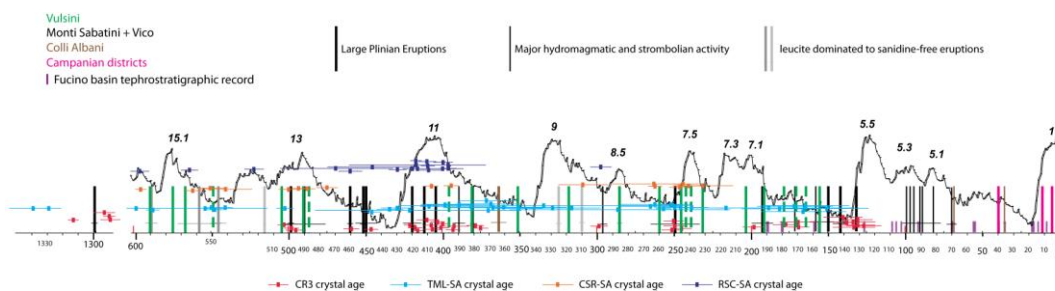
784 Youngest crystal ages of 232 ± 20 and 298 ± 4 ka yielded by sedimentary samples collected in
785 the alluvial facies (coastal plain) of the 51-57 m and of 71-79 m paleo-surfaces (CSR-SA and
786 RSC-SA) support correlation with MIS 7 and MIS 9 for the corresponding coastal terraces,
787 ~~respectively~~, as discussed in the following sections.

788 Similarly, crystal ages of the samples collected ~~in~~ ~~from~~ the backbeach facies at the top of the
789 98-108 m and 61-67 m paleo-surfaces provide time constraints on the sedimentary processes
790 that acted in the time span following retreat of the coastline leading to progressive
791 ~~pauperization~~ ~~impoverishment~~ of sediment supply.

792

793

794



795
 796 Figure 13 - Crystal age spectra for the four sedimentary samples dated in the present study.
 797 Each cross represents the age of one dated sanidine crystal with the associated analytical
 798 error at 2 σ . Comparison with the major eruptions occurred at the districts of the Roman Co-
 799 magmatic province is provided. Each bar represents one eruption age (see Suppl. Mat. for
 800 details and references). Comparison with the Oxygen-oxygen isotopes curve (Lisiecki and
 801 Raymo, 2005) is also shown. See text for comments.
 802

803 These age constraints are obtained by comparing the sample crystal ages with the eruptive
 804 histories of the volcanoes of the Latium Region, as provided in Figure 13. In considering the
 805 eruptive histories of the volcanic districts of Central Italy to compare age spectra yielded by
 806 the analyzed sedimentary samples reported in Figure 13, some preliminary considerations
 807 should be made.

808 i- These volcanoes are part of the "Roman Magmatic Province" (Conticelli and Peccerillo,
 809 1992), characterized by a K-rich geochemistry which accounts for the diffuse presence of
 810 sanidine ($KAlSi_3O_8$) and leucite ($K[AlSi_2O_6]$) crystals, which also constitute the means of
 811 $^{40}Ar/^{39}Ar$ dating. However, while sanidine is a very resistant mineral species, leucite is highly
 812 sensible to weathering and easily ~~turns out in alters~~ to analcime ($NaAlSi_2O_6$): a ~~n-alteration~~
 813 process implying loose of K and ~~hindering possibility of compromising~~ $^{40}Ar/^{39}Ar$ dating.

814 Indeed, fluviually transported and beach deposits of several hundred kyr lack ~~of~~ pristine leucite
 815 crystals. Therefore, in Figure 13 we have not reported all the sanidine-free eruption units (i.e.,
 816 most of those of the Colli Albani volcanic district, see Gaeta et al., 2016 and references
 817 therein), while we have indicated those dominated by leucite (for which a lesser statistical
 818 occurrence is expected).

819 ii- When incorporation of crystals ~~deriving derived~~ from primary fallout deposits is
 820 considered, the overall eastward regional winds and a consequent dispersal axis should be
 821 considered, along with the ~~vent~~ distance ~~from the source area~~. Therefore, the major source of
 822 fallout deposits are the MSVD and Vico, while deposits from the Colli Albani and the
 823 Campanian districts have ~~a~~ low probability ~~to be of represented representation~~ in the
 824 stratigraphic record. ~~It makes exception t~~ One exception is represented by the sanidine-
 825 bearing activity of the Albano Center spanning 70 through 36 ka (Giaccio et al., 2009, and ref.),

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826 | for which the small vent distance should ~~grant~~ have led to a well-represented crystal
827 | population, as also evidenced by outcrops in the southeastern area of the CAVD (e.g., Cisterna
828 | di Latina, Latina Plain; Gatta et al., 2018, Sevink et al., 2018). Moreover, huge explosive
829 | eruptions like the Campanian Ignimbrite (39 ka), Neapolitan Yellow Tuff (12 ka) and Avellino
830 | pumice (4 ka) have provided widespread tephrostratigraphic markers in Latium (e.g., Giaccio
831 | et al., 2017).

832 | iii- ~~Youngest~~ The youngest eruptions should be ~~more~~ better represented given the ~~largest~~
833 | larger outcropping areas of the products ~~with respect in to~~ comparison with the older ones,
834 | which are buried under more recent cover. ~~Thus~~ This reinforcing reinforces the principle that
835 | a lack of crystals younger than the youngest population is evidence of deposition prior to
836 | evidences a deposition time preceding age of the immediately following eruption.

837 | Consistent with the considerations above, Figure 13 shows that the age spectra of sanidine
838 | crystals extracted from the four sand samples record a long eruptive history, ranging 0.60 -
839 | 0.13 Ma, plus one isolated cluster around 1.3 M. All crystal ages ≤ 0.6 Ma match known
840 | eruption ~~occurred at~~ s of the Monti Sabatini, Vico and Vulcini volcanoes (Palladino et al., 2010;
841 | Sottili et al., 2010; Marra et al., 2014, and ref. therein), while the oldest age matches that of
842 | early activity ~~occurred at~~ of the Cimini volcanic complex (Everdin and Curtis, 1965, Nicoletti,
843 | 1969), located in the upper Tiber Valley east of Vico. In contrast, all the ~~missing literature~~
844 | eruption ages known from the literature that are missing in the dated crystal populations,
845 | besides the sanidine-free Colli Albani products, also correspond to sanidine-free or leucite-
846 | dominated products from Vico and Monti Sabatini volcanic districts (Cioni et al., 1987; Sottili
847 | et al., 2004; Perini et al., 2004; Masotta et al., 2010; Marra et al., 2014).

848 | Based on these premises, in the following we discuss sample age implications on assessing
849 | the age of the related paleo-surfaces.

850

851 | **5.2.1 CSR-SA - 51-57 m paleo-surface**

852 | Based on the sedimentary features of the underlying deposits and the top elevation ranging
853 | 51-57 m a.s.l. (Figure 9a-a"), the Castel Romano paleo-surface is interpreted as a backbeach
854 | context, including the dune system superimposing the delta plain, developed during
855 | highstand of MIS 7.3/7.1. Loose sanidine crystals occurring in the sand deposit of the braided
856 | fluvial channel facies (Figure 9a'-a") yielded a youngest age of 232.3 ± 19.8 ka, part of a
857 | statistically significant youngest population of 244.0 ± 3.8 ka (Table 4). Such datum has to be
858 | considered a terminus post-~~quem~~ ~~terminus~~ which implies an age \leq MIS 7.5 (Figure 13),
859 | excluding and age within MIS 9 and supporting correlation with highstand of the MIS 7.3/7.1.

860

861 5.2.2 RSC-SA - 71-79 m paleo-surface

862 ~~Age-~~The age spectrum of sample RSC-SA, collected within the alluvial plain deposit underlying
863 the 71-79 paleo-surface ~~in at~~ Riserva Carpineto, spans 581 - 398 ka, with a youngest crystal of
864 298 ± 3.5 ka (Table 4). Most crystal ages are clustered between 460 and 390 ka, coincident
865 with the large explosive phases emplacing sanidine-bearing products at Vico and Sabatini in
866 this time span (Figure 13). In contrast, no crystal deriving from the Villa Senni eruption unit
867 occurs in the dated sample, despite the sampled deposit overlies the Pozzolanelle eruption
868 unit of 365 ± 4 ka, consistent with the lack of sanidine phenocrystals in the Colli Albani
869 products. The age of one single crystal yielding 298 ± 3.5 ka has a poor statistical weight, and
870 should be regarded as broadly indicative of the lack of crystals younger than 300 ka. However,
871 it supports correlation with MIS 9 for the 71-79 m paleo-surface of Riserva Carpineto,
872 suggesting that sedimentation in the alluvial plain was sealed in the late stages of ~~the~~ MIS 9
873 highstand, excluding an age within MIS 7, while an age within MIS 11 is ~~also~~ excluded by the
874 fact that the sand deposit of Riserva Carpineto overlies the 365 ± 5 ka Pozzolanelle pyroclastic-
875 flow deposit.

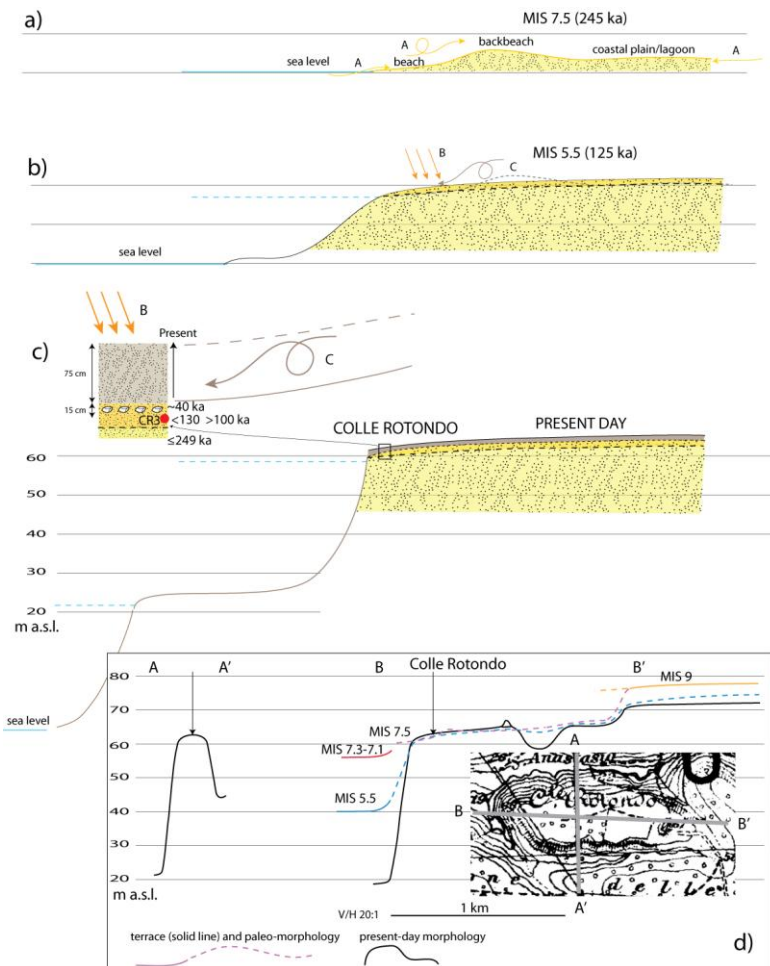
876

877 5.2.3 CR3 - 61-67 m paleo-surface

878 Based on its sedimentologic features and the elevation ranging 61-67 m a.s.l., the Colle
879 Rotondo paleo-surface is interpreted as a backbeach context, either part of a dune system or
880 of a coastal alluvial plain, developed during highstand of MIS 7.5 (Figure 14a).
881 When the crystal ages from CR3 (red crosses in Figure 13) are compared to the eruptive
882 histories of the volcanoes of the Latium Region, it is apparent that no eruption younger than
883 134 ± 3.5 ka is recorded by the Colle Rotondo sand deposit. Indeed, given the large number of
884 dated crystals (39) and the wide age spectrum observed, the lack of any crystal from the
885 eruptive activity since 99 ka (see Figure 13) strongly suggests that the sample age should be
886 constrained between 132 and 99 ka. In particular, a large hydromagmatic phase occurred ~~at~~
887 ~~in~~ several volcanic centers ~~at of~~ the MSVD, including Baccano, Stracciapappe, Le Cese,
888 Acquarello, Piana dei Falliti and Martignano, 132 ± 2 through 70 ± 3 ka (Sottili et al., 2010;
889 Marra et al., 2019b). While the earliest eruption ~~that~~ occurred at Baccano ~~at~~ 132 ± 2 ka is
890 evidently recorded by sample CR3, the lack of crystals from any ~~other successive later~~
891 eruption strongly suggests a ~~terminus~~ ~~ante-quem-terminus~~ of ca. 99 ± 3 ka (age of the
892 products of the 2nd Baccano unit, erupted at the beginning of the multi-vented
893 hydromagmatic activity ~~enduring that continued~~ until 70 ± 3 ka). Although this age boundary

894 to the deposit is in conflicting with the attribution to the Uluzzian for the lithic industry
 895 recovered at Colle Rotondo (Villa et al., 2018), we remark-note that sample CR3 was not
 896 collected in the stratum in conjunction with the artifacts, but in a side excavation. Therefore,
 897 its correspondence with the archaeological layer is not safely established and provenance
 898 may be from the immediately underlying older substrate. In this latter case, the occurrence of
 899 the Uluzzian lithic assemblage at ca. 80 cm depth suggests that the overlying package of
 900 sediment accumulated during the last 40 ky. Such an accelerated accumulation may be linked
 901 with recent anthropic activity (e.g., agriculture), triggering soil mobilization. In contrast, the
 902 apparent age of ~134 ka for the sand layer at 80 cm depth is-does not conflict~~ing~~ with an
 903 inferred age of 250-200 ka within MIS 7 for the Colle Rotondo paleo-surface, as discussed
 904 hereby based on a detailed analysis of and when results of the $^{40}\text{Ar}/^{39}\text{Ar}$ experiments dating
 905 are examined in detail, they give insights on its actual age and on the sedimentary processes
 906 that superintended to its formation results.

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907

908 Figure 14 - Geomorphological and paleogeographic evolution of the Collo Rotondo plateau
909 (see text for step by step comment and explanation).
910
911 Like in the case of the sedimentary deposit sampled ~~in~~at Castel Romano which yielded a
912 youngest crystal age of 232 ± 20 ka, consistent with a deposition age corresponding to the
913 highstand of MIS 7.3-7.1 (i.e. 220-200 ka), an age ≥ 245 ka is expected for the fluvial/beach
914 sedimentary deposit ~~from~~at Colle Rotondo (supply A in Figure 14a) incorporating crystals
915 ~~deriving~~derived from erosion and re-deposition of the volcanic rocks erupted ~~until~~before
916 that time, corresponding to highstand of MIS 7.5 (i.e., 245 ka, see Figure 13). However, a
917 progressively younger age is expected for the backbeach deposit deriving from mixing of
918 wind-blown sediment previously deposited (supply C in Figure 14b) with crystals deriving
919 from primary eruptions occurring in the following time span (supply B in Figure 14b). Sample
920 CR3 from Colle Rotondo yielded a statistically significant (8 crystals) youngest crystal
921 population of 134.2 ± 3.5 ka which is characterized by significantly larger associated errors
922 ~~with respectin~~to comparison with the older populations (see Table 5). In particular, these
923 crystals yielded an average associated error of ± 11 ka (corresponding to 8.2% when an age of
924 134 ka is considered) ~~with respectin~~to comparison with an average associated error of ± 5.4
925 ka for the 23 crystals yielding ages spanning 249.9 - 503.2 ka (corresponding to 2.2% - 1.1%).
926 These larger errors are due to the systematically smaller dimensions of these crystals,
927 evidencing their different means of transport ~~with respectin~~to comparison with that affecting
928 the oldest ones, i.e.: wind vs. water. When this distinction is ~~noticed~~taken into account, we
929 find a second significant population age of 249.3 ± 3.4 ka, along with a few crystal ages ranging
930 200-170 ka (Table 4 and Figure 13), consistent with an age within MIS 7.5 for the original
931 beach/alluvial deposit. An age $\geq 134 \pm 3.5 \leq 198.4 \pm 7.3$ ka is established for the sampled
932 backbeach deposit, showing that it accumulated above the MIS 7.5 paleosurface ~~for~~during ca.
933 110 ky (i.e., 245 through 134 ka). The lack of crystals deriving from the eruptions ~~occurred~~
934 between 132 ~~through and~~ 70 ka at the MSVD (see Figure 13), strongly suggests that the
935 sampled layer cannot be younger. Indeed, accidental ~~lacking~~absence of crystal ages within
936 this time span is statistically unlikely, given the eastern dispersal axis of the MSVD eruption
937 (e.g. Sottili et al., 2004; Di Rita and Sottili, 2019) and the occurrence of large explosive
938 eruptions 90 through 70 ka at a number of centers of the so-called "Hydromagmatic Phase"
939 (De Rita et al., 1983; Sottili et al., 2010; Marra et al., 2019b). This fact also testifies that the
940 depositional context progressively changed after 245 ka, consistent with continued uplift of
941 the coast and isolation of the Colle Rotondo remnant paleo-surface, which was unaffected by
942 deposition of water transported sediment, like that occurring in alluvial plain or beach

943 contexts, while only eolian fallout deposits were emplaced, from then on. Since sample CR-1
944 occurs 90 cm below the present ground level (Figure 14c), we can infer that present elevation
945 of 63 m is a close approximation of the MIS 7.5 paleo-surface, which is overlain by a thin
946 eolian deposit accumulated since 245 ka ~~through the Present~~ (input B in Figure 14c). Indeed,
947 it is likely that samples collected closer to the surface would yield progressively younger ages,
948 consistent with incorporation of crystals deriving from the younger eruptions of 100 ka and
949 90 through 70 ka. However, the strong anthropic disturbance of the upper 70 cm of sediment
950 prevents any reliable analysis. Sample TML-SA from Tenuta Monte di Leva section provides
951 further inferences on the formation process of this thin eolian cover of the paleo-surfaces.
952

953

954

CR3	
Age (ka)	$\pm 2\sigma$ (ka)
134,0	$\pm 14,3$
133,4	$\pm 13,7$
140,6	$\pm 12,5$
169,7	$\pm 11,7$
127,7	$\pm 11,3$
130,9	$\pm 11,2$
131,7	$\pm 9,7$
131,0	$\pm 9,6$
392,9	$\pm 9,6$
177,6	$\pm 8,3$
198,4	$\pm 7,3$
249,9	$\pm 7,2$
169,5	$\pm 6,9$
1293,0	$\pm 6,9$
245,3	$\pm 6,6$
251,6	$\pm 6,6$
250,7	$\pm 6,5$
410,7	$\pm 6,5$
495,5	$\pm 6,5$
1289,3	$\pm 6,5$
138,3	$\pm 6,3$
298,9	$\pm 5,6$
379,1	$\pm 5,6$
407,3	$\pm 5,6$
401,4	$\pm 5,1$
459,2	$\pm 5,1$
375,6	$\pm 4,9$
393,5	$\pm 4,8$
498,4	$\pm 4,8$
403,6	$\pm 4,7$
400,2	$\pm 4,6$
407,8	$\pm 4,6$
418,1	$\pm 4,6$
446,8	$\pm 4,6$
503,2	$\pm 4,1$
1289,9	$\pm 3,9$
421,7	$\pm 3,8$
416,5	$\pm 3,5$
1313,1	$\pm 3,5$
youngest population:	
134,2	$\pm 3,5$

955

956

TML-SA	
Age (ka)	$\pm 2\sigma$ (ka)
335,5	$\pm 96,7$
287,5	$\pm 72,5$
422,9	$\pm 63,3$
189,3	$\pm 54,3$
361,0	$\pm 40,6$
557,0	$\pm 40,2$
368,2	$\pm 32,7$
165,5	$\pm 28,5$
166,6	$\pm 27,9$
151,1	$\pm 27,6$
181,7	$\pm 25,4$
171,0	$\pm 24,9$
382,2	$\pm 23,2$
389,6	$\pm 23,0$
262,8	$\pm 22,7$
371,2	$\pm 21,5$
329,8	$\pm 20,8$
266,0	$\pm 20,0$
369,5	$\pm 20,0$
316,8	$\pm 18,7$
372,6	$\pm 18,7$
246,2	$\pm 17,8$
398,9	$\pm 16,2$
1339,3	$\pm 15,9$
351,5	$\pm 15,7$
430,5	$\pm 10,9$
435,7	$\pm 8,7$
1328,9	$\pm 8,0$
252,3	$\pm 7,1$
250,0	$\pm 6,6$
600,0	$\pm 6,4$
216,5	$\pm 6,0$
409,6	$\pm 5,9$
446,4	$\pm 5,6$
504,4	$\pm 5,6$
549,4	$\pm 5,4$
257,6	$\pm 5,1$
541,7	$\pm 5,0$
239,9	$\pm 4,7$
589,3	$\pm 4,4$
551,8	$\pm 4,3$
youngest population:	
169	± 11

957

958

959

960

961

962 Table 5

963

964

965

966

CSR-SA	
Age (ka)	$\pm 2\sigma$ (ka)
263,7	$\pm 29,1$
232,3	$\pm 19,8$
542,1	$\pm 17,2$
310,1	$\pm 16,3$
805,2	$\pm 9,7$
552,1	$\pm 9,0$
240,9	$\pm 8,2$
476,6	$\pm 7,1$
246,8	$\pm 6,9$
500,8	$\pm 6,8$
625,7	$\pm 6,7$
563,1	$\pm 6,2$
244,5	$\pm 5,7$
488,3	$\pm 5,3$
395,5	$\pm 5,0$
494,5	$\pm 4,7$
263,1	$\pm 4,6$
407,9	$\pm 4,4$
597,3	$\pm 3,7$
508,5	$\pm 3,5$
youngest population:	
244	± 4

967

968

969 5.2.4 TML-SA - 98-108 paleo-surface

970 Much caution should be used in interpreting results for the TML-SA sample because it ~~is-was~~
971 collected ca. 60 cm below the ground level within the soil horizon, in which both vertic
972 processes and anthropic disturbance might have caused incorporation of younger crystals
973 ~~coming~~ from the uppermost portion of the stratum.

974 However, ~~the~~ age spectrum of sample TML-SA, collected on the 98-108 paleosurface, is similar
975 to that of CR3 but yields a youngest minimum age of 169 ± 11 ka (Figure 13), evidencing a
976 relative older age, with respect to the sample collected on the 61-67 paleosurface of Colle
977 Rotondo.

978 These data suggest that the sampled sand deposit represents a sedimentary horizon that was
979 sealed from air-fall input by 170 ka, supporting the notion that the uppermost portion of the
980 reconstructed paleo-surfaces represents an accretionary horizon, built up mainly through
981 accumulation of alluvially/colluvially transported and, subordinately, air-fallen material.
982 Remarkably, also in this sample the youngest crystal population is characterized by larger
983 associated errors (Table 5), supporting the different mean of transport for this sedimentary
984 fraction which accumulated later, as ~~an air-fallen~~ deposit above the underlying deposits of the
985 alluvial plain.

986 The very low sedimentation rate and the limited thickness of these accretionary horizons
987 overlying the "pristine" deposit ~~originats forming~~ the paleosurfaces, whose absolute age has
988 been determined by $^{40}\text{Ar}/^{39}\text{Ar}$ dating on "in stratum" samples from Castel Romano and
989 Riserva Carpineto, is consistent with the geomorphologic features of the TML and CR sectors,
990 ~~preventing-precluding~~ significant alluvial/colluvial sedimentation.

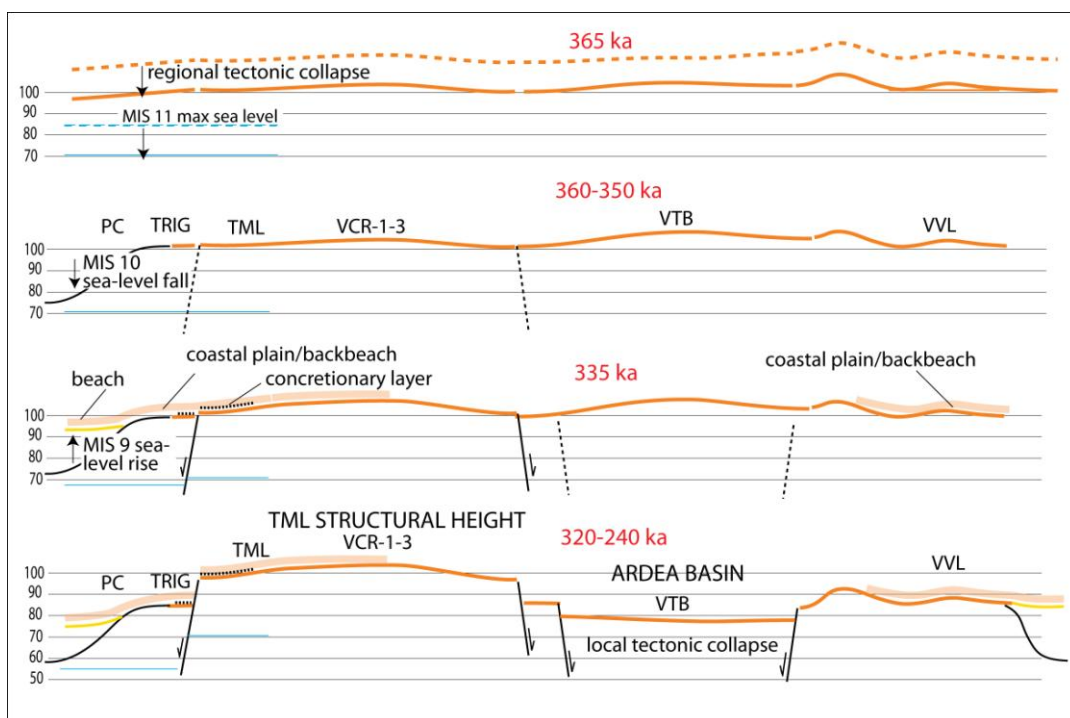
991

992 5.3 The MIS 9 paleo-surface

993 Geomorphological, lithostratigraphic, paleo-environmental and geochronological constraints
994 ~~provided-obtained for~~ the deposits of the 71-79 m paleo-surface, and part of the 80-89 m
995 and 98-108 m paleo-surfaces, allow ~~at-the identifying-identification of~~ these paleo-surfaces as
996 the remnant coastal terrace of the MIS 9 highstand, tectonically dislocated (Figure 11 and 15).

997 The subrounded morphology, the medium to coarse grain-size and the ~~good-high degree of~~
998 sorting of the sand deposits ~~of-at~~ Riserva Carpineto (RSC) clearly indicate that the flat sectors
999 at elevations ranging 71-79 m a.s.l. represent remnant ~~shreds-parts~~ of an alluvial coastal plain,
1000 stretching NW to SE parallel to the present coastline (Figure 11 and 12a3). Crystal ages
1001 yielded by sample RSC-SA firmly constrain the formation of this coastal plain within MIS 9
1002 (see also Figure 16). The bedded deposits of Campo di Carne (CDC), ranging from coarse sand

1003 to silty clay, are suggestive of a coastal alluvial plain, overlain by a transgressive backbeach
 1004 deposit forming a wide dune ridge system culminating at ca. 85 m a.s.l. in this area (Figure 11
 1005 and 12a3), and equivalent to that occurring in Trigoria (TRIG) at analogous elevations (Figure
 1006 11 and Figure 12a1). Evidence from the Tenuta Monte di Leva (TML) site shows that this
 1007 backbeach setting homogeneously extends parallel to the paleo-coastline, but it is presently
 1008 displaced at to an ca. 20 m higher elevation in this sector (Figure 15). Micromorphological
 1009 analysis on of the ~~concretion~~concretionary layer observed in the TML evidence indicates
 1010 that this massive horizon formed in alluvial to backbeach environment characterized by a
 1011 water table close to the surface, consistent with the reconstructed paleogeographic
 1012 conditions, which indicates show that it was part of the coastal plain. The geologic substrate in
 1013 at TML is indeed identical to that in at TRIG, apart from the larger thickness of the upper,
 1014 aeolian sand horizon above the ~~concretion~~concretionary layer in at the latter location,
 1015 consistent with a post-depositional tectonic displacement between these two sectors and
 1016 limited erosion occurred in at TML.



1017
 1018 Figure 15 - Palimpsestic reconstruction of the tectonic evolution of the coastal sector between
 1019 the Tiber mouth and Anzio in the time span 365 ka (age of emplacement of the Villa Senni
 1020 Eruption Unit during lowstand of MIS 10) and 240 ka (onset of MIS 7.5). a) A regional collapse
 1021 immediately following emplacement of the pyroclastic flow-deposit is inferred by from the
 1022 elevation gain between the top surface of aggradation successions of MIS 11 and MIS 9.
 1023 MIS 11. b) Erosion of the original paleo-surface occurs during the lowstand of MIS 10, 360

1024 through 350 ka. c) Fluvial and coastal incisions are filled by sediment-aggradation during
1025 glacial termination ~~v-V (335 ka) at the onset of the sea-level rise during MIS 9 (335 ka)~~, and as
1026 coastal setting including a beach to backbeach and coastal plain environment ~~is formed forms~~
1027 during ~~the~~ MIS 9 highstand (325 ka). d) This homogeneous coastal setting is disrupted by
1028 fault displacement ~~originating forming~~ a structural high in ~~the~~ TML and a collapsed sector
1029 (Ardea basin) ~~in during~~ the time span 320-240 ka (MIS 7.5 highstand) as ~~provided indicated~~
1030 by the upper chrono-morphological constraint represented by the inner edges of MIS 7.5
1031 coastal terrace (see text for further explanation).
1032

1033 On the other hand, the 98-108 m paleo-surface represents a striking geomorphological anomaly
1034 bordering the Ardea Basin to the NW (see also Figure 4), and is clearly interpretable as the
1035 result of differential uplift at the footwall of ~~one a border boundary~~ fault of the half-graben
1036 structure (Figure 11 and 15). Also the different geologic substrate that characterizes the 71-
1037 79 m paleo-surface within the Ardea Basin (e.g., VTB), which is formed by volcanic deposits
1038 (i.e.: the same substrate ~~of as~~ the inland portion of the 98-108 m paleo-surface in VCR 1-2), is
1039 suggestive of tectonic lowering following the formation of a homogeneous coastal ~~setting~~
1040 ~~platform~~ during ~~the~~ highstand of MIS 9, throughout this region. ~~Differently In contrast~~, in ~~the~~
1041 case of a pre-existing ~~gulf embayment~~ in this area, the 71-79 m paleo-surface ~~in at~~ VTB should
1042 have had the same sedimentary substrate as that occurring in PC and RSC, ~~testifying~~
1043 ~~confirming~~ a coastal environment. In particular, the tectonic collapse of the Ardea Basin is
1044 constrained between 320 ka (end of ~~the MIS 9 highstand of MIS 9~~) and 240 ka (highstand of
1045 MIS 7.5) (Figure 15), as provided by the geometry of the 60-67 m and 51-57 m coastal
1046 terraces, ~~evidencing indicating~~ that a ~~gulfn embayment~~ formed by the time of establishment of
1047 the new coastline during MIS 7.5 through MIS 7.1 (see Figure 3 and 4). Remarkably, this time
1048 span is coincident with the occurrence of the Monte delle Fate phase of activity at the Colli
1049 Albani Volcanic district (Gaeta et al., 2016, and references therein).
1050

1051 5.4 MIS 7.5 paleo-surface

1052 The ~~safe-secure~~ correlation with MIS 9 for the coastal plain deposits of the 71-79 m
1053 paleosurface, combined with previous geochronologic constraints ~~that frame the 51-57m~~
1054 ~~paleosurface on the 51-57 m paleosurface framing it~~ within the broad MIS 7.5 - MIS 7.1
1055 interval (Figure 16a), suggests that the intermediate 61-67 m surface should be correlated
1056 with the early interglacial 7.5, while the paleo-surface occurring a few meters below, at ~~an~~
1057 elevation of 51-57 m, should be correlated with the ~~latest later~~ isotopic peaks ~~7.13-/7.3-1~~
1058 which are not separated by a marked sea-level fall (See Figure 16a), and can be regarded as a
1059 single eustatic event. Crystal age distribution yielded by sample CR3 from Colle Rotondo

1060 supports this correlation (Figure 16b). Based on the considerations reported above on the
1061 errors associated with the $^{40}\text{Ar}/^{39}\text{Ar}$ ~~experiment dating~~ and their direct relation with grain-
1062 size, we can infer that an alluvial coastal plain formed by 249.3 ± 3.4 ka, an age remarkably
1063 coincident with glacial termination III at the onset of MIS 7.5 (Figure 16b), at ca. 60 m a.s.l.. It
1064 was successively mantled by ~~a~~ wind-blown deposit ~~coming derived~~ from the nearby beach ~~in~~
1065 ~~during~~ the interval 200 - 170 ka, a time when the coastline re-~~approached~~~~bounded to the~~
1066 elevation of 60 m a.s.l. during sea-level high stands linked with the double peak in the isotopes
1067 curve of MIS 7.3 and 7.1. Indeed, according to geomorphologic reconstruction, sedimentologic
1068 features, and micromorphologic analysis, the Colle Rotondo sand is a backbeach deposit. The
1069 sand grains originated mainly from very ~~short-proximal~~ aeolian transport from the beach,
1070 where the original sediment accumulated after being eroded and transported by the Tiber
1071 River and its tributaries (A in Figure 14a). Moreover, since formation of the dune ridge, more
1072 ~~aeolian~~ material, as well as primary, air-fallen volcanic deposits (including sanidine minerals,
1073 B in Figure 14a), accumulated above it. Eventually, this sector was isolated from the coastal
1074 environment by the continued uplift, and it was affected only by deposition of the syn-
1075 eruptive fallout deposit of the Baccano unit ~~occurred at~~ 132 ± 2 ka. If we consider the strong
1076 uplift of more than 50 m ~~that~~ occurred ~~since from~~ 250 ka, the wind-blown depositional
1077 mechanism ~~rapidly~~ became ~~soon~~ ineffective, due to the increased elevation-~~gain~~ and distance
1078 from the coastline (e.g., by 125 ka, Figure 14b). The regional uplift, determining the deep
1079 ~~cutting-incision~~ of the coastal terrace through the action of fluvial erosion, also ~~originated~~
1080 ~~generated~~ the canyon-like morphology that characterizes this area, isolating the Colle
1081 Rotondo plateau and preventing alluvial sedimentation on its top (Figure 14c-d). Therefore, it
1082 is reasonable to assume that a very limited thickness of sediment accumulated above the
1083 original paleo-surface representing the coastal terrace, mainly by ~~the~~ air-fall mechanism and
1084 only subordinately, as a consequence of re-mobilization of pre-existing sediment, through
1085 wind transport, or water run-off and colluviation from the upper part of the plateau towards
1086 the lower sectors (C in Figure 14b). If we consider that the elevation gain between the top and
1087 the margins of the Colle Rotondo plateau is less than 4 m (Figure 14d), the latter depositional
1088 mechanisms must have acted in ~~a~~ very limited way.

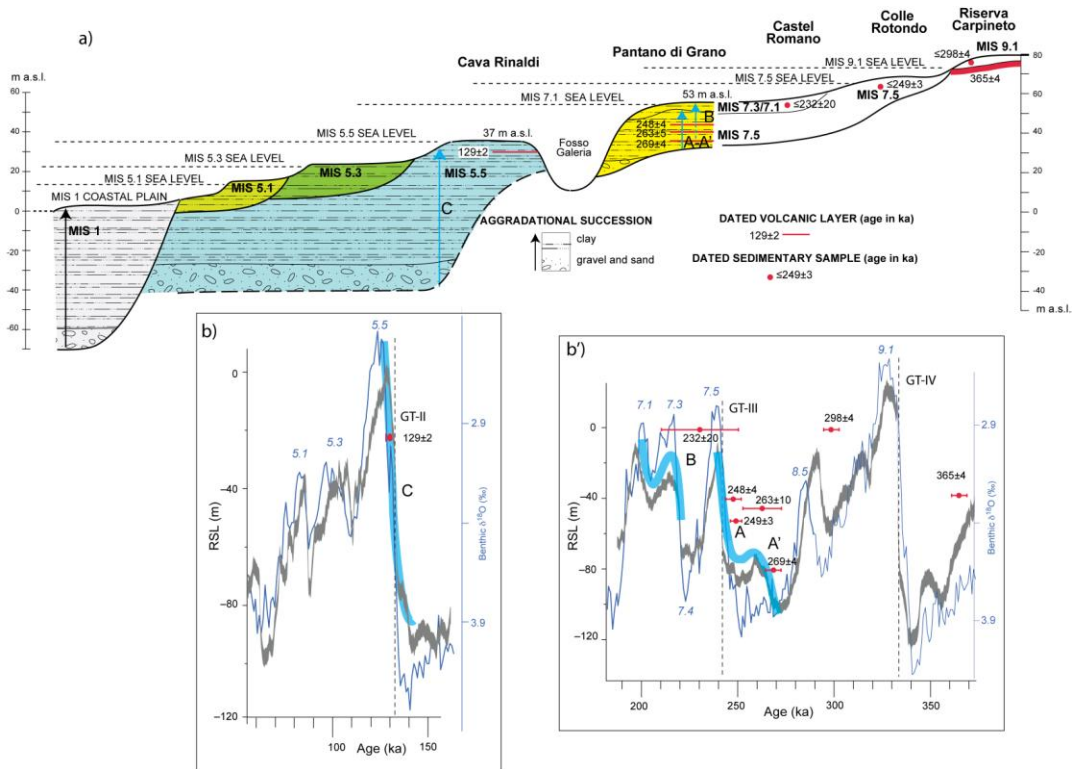
1090 5.5 MIS 7.3-7.1 paleo-surface

1091 The 51-57 m paleo-surface previously detected ~~in by~~ Marra et al. (2016) has widespread
1092 expression ~~in at~~ Ponte Galeria (Fig. 2), where chronostratigraphic constraints on the
1093 underlying aggradational deposits (Vitinia Formation, Luberti et al., 2017 and references

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1094 therein) and their geometric/stratigraphic relationship with the 36 m terrace unambiguously
 1095 provide correlation with the four-stepped sea-level rise that characterized MIS 7 (Marra et al.,
 1096 2016b). In particular, an early aggradational phase of the Vitinia Formation around 269 ka
 1097 matches a first the initial sea-level rise (A' in Fig. 16b) preceding the marked sea-level jump of
 1098 glacial termination III that occurred at 240 ka, to with which in turn is associated the main
 1099 aggradational succession of MIS 7.5, bracketed by post-quem ages of 253 ± 8 ka and 248 ± 4 ka
 1100 (A in Fig. 16b).



1101
 1102 Figure 16 - a) Idealized cross-section reconstructing the terraced deposits and the
 1103 corresponding aggradational successions in the investigated coastal sector, showing the
 1104 geochronologic constraints providing correlation with MIS 9.1 through MIS 5.5. b-b') Ages of
 1105 the dated volcanic deposits and reworked crystal populations (red dots, bars indicate the
 1106 analytical error at 2σ) are compared with the Oxygen isotope curve (Lisiecki and Raymo,
 1107 2005) and the Relative Sea Level (RSL) curve (Grant et al., 2014). Correspondence of sediment
 1108 aggradation with the phases of fast rapid sea-level rise (thick blue lines) during the glacial
 1109 terminations (GT) is highlighted.
 1110

1111 Finally, a marked unconformity cuts the deposits of MIS 7.5 aggradational succession and is
 1112 overlain by a new aggradational succession that represents the sedimentary deposit forming
 1113 the flat top of the hills constituting the relict paleo-surface of 56-52 m a.s.l. The intervening
 1114 erosional phase and the following sediment aggradation evidently match the sea-level fall of

1115 MIS 7.4 and the successive two-stepped sea-level rise of MIS 7.3 - MIS 7.1 (Marra et al., 2016b;
1116 B in Fig. 16b). This observation corroborates the new assessment of the 51-57 m paleo-
1117 surface, and its attribution to the later stages of MIS 7.3/7.1, rather than to MIS 7.5, as shown
1118 by correlation provided in cross-section of Figure 16a.

1119

1120 **5.6 MIS 5.5 - 5.3 - 5.1 terraces**

1121 The occurrence of a suite of three lowest ~~orders-of~~ coastal terraces has been shown by
1122 geomorphologic reconstruction of their relict surfaces provided ~~in-by~~ Marra et al. (2016a,
1123 2019a), who also demonstrated that three distinct successions of coastal plain sediments,
1124 corresponding to three coastlines at circa 34, 24 and 12 m a.s.l., are associated with these
1125 terraces (Figure 16a). The $^{40}\text{Ar}/^{39}\text{Ar}$ age of 129 ± 1 ka on a pyroclastic-flow deposit
1126 intercalated within the aggradational succession forming the 36 m terrace ~~in-at~~ Cava Rinaldi
1127 (Epi-Tyrrhenian Formation, Marra et al., 2015) demonstrated correlation with the MIS 5.5
1128 highstand of 125 ka (Figure 16b'). The two lower terraces at 26 and 16 m were therefore
1129 tentatively correlated with the sea-level highstands of MIS 5.3 and 5.1, respectively. However,
1130 an intervening tectonic collapse of ca. 10 around 100 ka, interrupting a steady uplift phase
1131 between 250 ka and the ~~Present-Holocene~~ had to be invoked by Marra et al. (2016a), in order
1132 to reconcile elevation of the terrace at 26 m with absolute sea-level established for MIS 5.3
1133 and 5.1 in the literature (e.g. Rohling et al., 2009). A discussion of the age of these terraces is
1134 beyond the scopes of the present paper, and further geochronologic and sedimentologic
1135 investigations of these youngest successions are in progress, aimed at verifying their exact
1136 correlation with the MIS timescale. However, in the present study we have found an excellent
1137 fit of the new geomorphological and statistical assessment of these paleo-surfaces with ~~the~~
1138 previous results ~~in-of~~ Marra et al. (2016a, 2019a), and we maintain preliminary correlation
1139 with the three marine isotopes' sub-stages of MIS 5.5, 5.3, and 5.1 in the discussion of the
1140 tectonic uplift.

1141

1142 **5.7 Tectonic implications**

1143 All the sea-level markers provided by the aggradational successions of the Paleo-Tiber River
1144 correlated with MIS 21 through MIS 1 from literature and from the present study are shown
1145 in Figure 17a. Differences in elevation among the different coastal deposits assumed as sea-
1146 level markers (green shading in Figure 17a) ~~is-are~~ the result of the intervening tectonic
1147 movement (uplift or collapse) combined with the difference in maximum sea-level at each
1148 interglacial (glacio-eustatic component). This latter element is estimated assuming a sea-level

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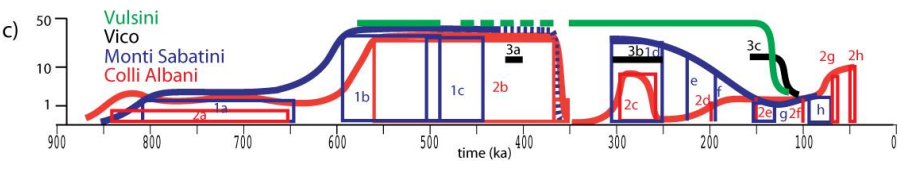
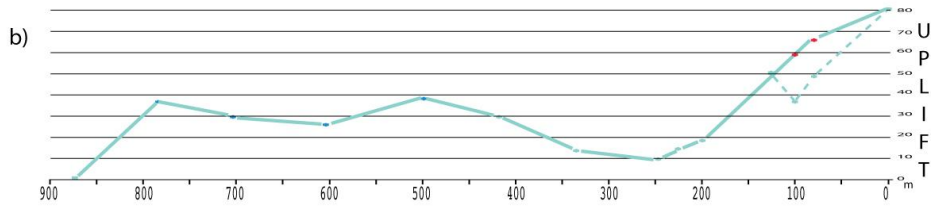
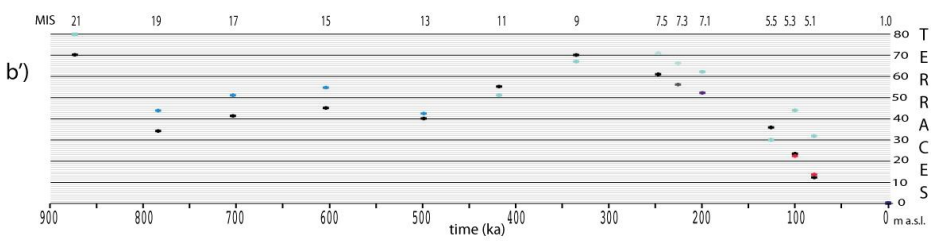
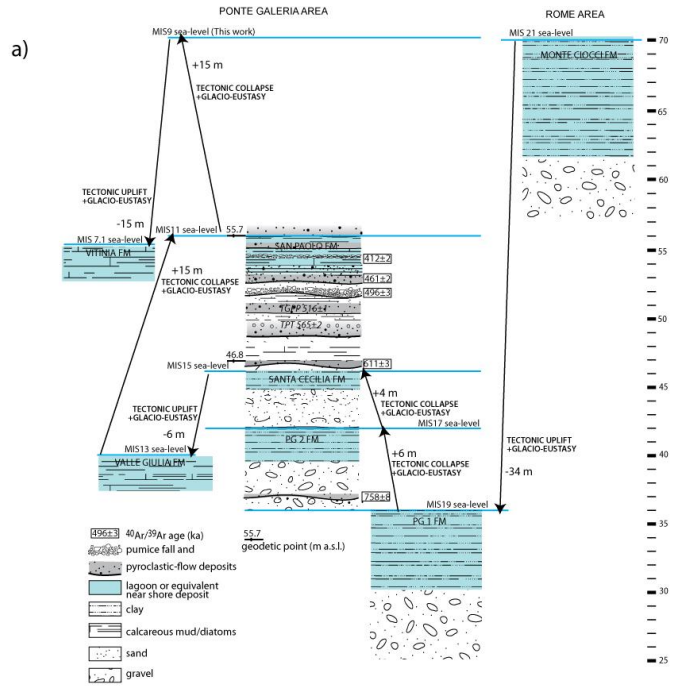
1149 10 m lower than ~~in the~~ present during MIS 21 through MIS 15 (blue crosses in Figure 17b')

1150 based on previous literature ~~data~~ (Marra et al., 2016 and references therein), while values

1151 estimated in Rohling et al. (2009) are considered for MIS 13 through MIS 5.1 (green crosses).

1152

1153



1154

1155 | Figure 17 - a) Synoptic ~~picture representation~~ of the different sections from the Rome's area
1156 | ~~exposing-indicating~~ the aggradational successions and related sea-level indicators correlating
1157 | ~~with~~ MIS 21 through MIS 7, integrating geochronologic and stratigraphic data from Karner
1158 | and Renne, 1998; Karner and Marra, 1998; Karner et al., 2001b; Marra et al., 1998; 2016b;
1159 | 2017a.
1160 |
1161 | Alternative values for MIS 5.3 and 5.1 (red crosses) are also used to assess the uplift curve for
1162 | the last 125 ka, based on the assumption of a more reliable uniform tectonic uplift in this time
1163 | span, and on recently provided geochronologic and geomorphologic constraints ~~to-on~~ the
1164 | related sea-level markers (Marra et al., 2016a, 2019a). Once the correction for the glacio-
1165 | eustatic component is applied, the cumulative uplift curve of Figure 17b is obtained. Similar to
1166 | previous work (Marra et al., 2016a, 2019b), comparison between the uplift curve and the
1167 | eruptive histories of the volcanic districts of the Roman Province is also provided (Figure
1168 | 17c). ~~With respect~~~~In comparison to~~~~with~~ previous reconstructions (e.g., Marra et al., 2016a)
1169 | this refined uplift curve displays a marked subsidence phase between 500 and 300 ka, as
1170 | provided by assessment of the MIS 9 sea-level markers at ca. 70 m a.s.l. ~~established~~
1171 | ~~established~~ in the present work (Figure 17a). This fact ~~enhances-reinforces~~ the coupling
1172 | already ~~remarked-noted~~ with the occurrence of two major phases of common volcanic activity
1173 | at Colli Albani and Monti Sabatini 850 through 650 and 600 through 350 ka. In particular,
1174 | uplift coincides with the onset of these phases, while subsidence characterizes the eruptive
1175 | time spans. The ~~subsiding subsidence~~ phase ~~endures-continued~~ until 250 ka and ~~also~~
1176 | encompasses ~~also~~ the ~~climactic-climax~~ phase that, after a ca. 50 kyr dormancy, occurred at
1177 | Vico, Monti Sabatini and Colli Albani, spanned the interval 320 - 250 ka, during which a
1178 | rejuvenation of the volcanic activity occurs ~~at~~~~red in~~ all the districts of central Italy (Marra et
1179 | al., 2004). The geochronologic constraints provided here ~~to-for~~ the MIS 7.5 and MIS 7.3/7.1
1180 | terraces allows ~~at~~~~defining a~~ better ~~definition of~~ the beginning of the most recent uplift phase
1181 | ~~since-post-~~250 ka, which is characterized by an initial low gradient followed by a steady, steep
1182 | increase 200 though 80 ka, and by a waning trend until the ~~Present-present~~ (solid green curve
1183 | in Figure 17b). As previously ~~remarked-noted~~, this new uplift phase heralds and accompanies
1184 | the latest volcanic phases ~~occurred-during~~ 90 - 70 ka at Monti Sabatini and 70-36 ka at Colli
1185 | Albani, and it has been suggested to be related ~~with-to~~ the onset of a new magmatic phase
1186 | extending from southern Latium to the Campanian districts of Phlegraean Fields and Vesuvius
1187 | (Mara et al., 2016a). In contrast, volcanic activity seems to ~~be~~ ~~have been~~ ~~extinguished~~
1188 | ~~extinguished at~~ in the districts of northern Latium (Vulsini, Vico) since 100 ka. However,
1189 | Marra et al. (2019a) have shown that this recent uplift phase ~~homogeneously~~ ~~hs~~ ~~affects~~

1190 | ~~affected~~ the whole coast of Latium ~~homogeneously, comprising the northern sector facing the~~
1191 | ~~Vulsini and Vico districts,~~ in apparent conflict with ~~the~~ lack of a new magmatic phase at these
1192 | volcanoes. In contrast, ~~extinguishment cessation~~ of the activity at Vulsini and Vico matches the
1193 | sudden tectonic collapse which is inferred when the current sea-level values for MIS 5.3 and
1194 | 5.1 are assumed (dashed portion of the uplift curve in Figure 17c). However, ~~hypothesizing~~ a
1195 | direct link between local volcanic activity in the northern sector and the global tectonic signal
1196 | in this region is unlikely. Moreover, recent geochronologic and geomorphologic data strongly
1197 | ~~support imply~~ that anomalous sea-levels characterized ~~the~~ MIS 5.3 and MIS 5.1 highstands in
1198 | the Mediterranean region, suggesting the unforeseen role played by Glacial Isostatic
1199 | Adjustment (GIA) on regional tectonics during the the post-glacial period (Marra et al.,
1200 | 2019a).

1201 | Future investigations ~~is~~ ~~needs to be addressed~~ in order to understand this complex
1202 | framework of vertical movement, volcanic activity and glacio-eustasy affecting the Tyrrhenian
1203 | Sea Margin during the last million years. Indeed, we ~~remark note~~ that beyond the common
1204 | assumption of a interconnection between subduction, volcanism and regional uplift in the
1205 | back-arc domain of the central Apennines (e.g., Conticelli and Peccerillo 1992), no dedicated
1206 | study aimed at ~~individuating evaluating~~ the geodynamic and isostatic forces responsible for
1207 | the observed tectonic uplift has been ~~addressed undertaken~~ so far.

1209 | **6. Conclusions**

1210 | Combined geomorphologic study and statistical analysis, ~~and together with~~ review and re-
1211 | analyses of previous ~~literature published~~ data, ~~have~~ allowed us to identify a set of paleo-
1212 | surfaces defined by discrete classes of elevation for topographic culminations in the coastal
1213 | Tyrrhenian Sea sector of central Latium.

1214 | We recognized eight such paleo-surfaces defined by the elevation ranges: 98-108, 80-89, 71-
1215 | 79, 61-67, 51-57, 30-43, 22-27, 11-17 m a.s.l..

1216 | The three lowest paleo-surfaces are narrowly elongated parallel to the coastline and were
1217 | identified through definition of the corresponding sea-level markers and geochronologic
1218 | constraints in previous studies as the marine terraces of MIS 5.5, 5.3 and 5.1, (Marra et al.,
1219 | 2016a, 2019a).

1220 | The highest five paleo-surfaces have been investigated here and their physical extension has
1221 | been validated through DEM analyses, in order to compare the results of the
1222 | geomorphological study on 1:25.000 topographic maps.

1223 The sedimentologic-stratigraphic features of the soils and of the sedimentary deposits
1224 forming these paleo-surfaces have been investigated ~~aimed in order~~ to define their
1225 paleogeographic context and to identify the sea-level markers for those which have been
1226 interpreted as remnant portions of coastal terraces.
1227 ⁴⁰Ar/³⁹Ar ages of detrital sanidine extracted from the sandy deposit of the recognized coastal
1228 ~~plain setting terraces~~ ~~has~~ allowed us to correlate the 71-79 m, the 61-67 m, and the 51-57 m
1229 paleo-surfaces with the coastal terraces formed during ~~the~~ MIS 9.1, MIS 7.5, and MIS 7.3/7.1
1230 highstands, respectively.
1231 ~~The paleogeographic reconstruction~~ ~~has~~ allowed us to interpret the 71-79 m, ~~the~~ 80-89 m,
1232 and ~~the~~ 98-108 m paleo-surfaces as ~~one a single~~ tectonically displaced, widespread coastal
1233 ~~setting platform originated formed~~ during ~~the~~ MIS 9.1 highstand.
1234 Based on ~~the~~ combination of our refined dataset of terrace elevations with ~~literature~~
1235 ~~published~~ data on relative elevation of maximum sea level during ~~the~~ highstands of MIS 21
1236 through MIS 5.1, we assess the regional uplift curve in the last 900 ka and ~~we~~ recognize the
1237 occurrence of a climactic extensional tectonic phase affecting this coastal sector between 320
1238 and 240 ka, coincident with occurrence of the Monte delle Fate phase of activity at the Colli
1239 albani Volcanic district.

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1243 **Supplementary Material #1**- 1:25.000 basemap with topographic culminations
1244 **Supplementary Material #2A**: Micromorphology: Methods - Fig. S1-S6
1245 **#2B**: X-Ray power diffraction methods **#2C**: SEM microphotographs - Fig. S7
1246 **Supplementary Material #2D** - Diffractograms
1247 **Supplementary Material #3a, b**: Full $^{40}\text{Ar}/^{39}\text{Ar}$ data.
1248
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1250 REFERENCES

- 1251
1252
1253 Barberi, F., Buonasorte, G., Cioni, R., Fiordelisi, A., Foresi, L., Iaccarino, S., Laurenzi, M.A.,
1254 Sbrana, A., Vernia, L., Villa, I.M., 1994. Plio-Pleistocene geological evolution of the geothermal
1255 area of Tuscany and Latium. Mem. Descr. Carta Geol. d' It. 49, 77-134
1256
1257 Bridgland, D.R., Westaway, R., 2008. Climatically controlled river terrace staircases: a
1258 worldwide Quaternary phenomenon, *Geomorphology* 98, 285-315.
1259
1260 Cioni, R., Sbrana A., Bertagnini, A., Buonasorte G., Landi, P., Rossi, U., Salvati, L., 1987. Laurenzi,
1261 M.A., Tephrostratigraphic correlations in the Vulsini, Vico and Sabatini volcanic successions.
1262 *Periodico di Mineralogia* 56, 137-155.
1263
1264 Conticelli, S., Peccerillo, A., 1992. Petrology and geochemistry of potassic and ultrapotassic
1265 volcanism in central Italy: petrogenesis and inferences on the evolution of the mantle sources,
1266 *Lithos* 28, 221-240.
1267
1268 De Rita, D., Funicello, R., Rossi, U., Sposato, A., 1983. Structure and evolution of the Sacrofano-
1269 Baccano caldera, Sabatini Volcanic Complex, Rome: *J. Volcanol. Geotherm. Res.* 17, 219-236.
1270
1271 De Rita, D., Faccenna, C. Funicello, R. Rosa, C., 1995. Stratigraphy and volcano-tectonics, in *The*
1272 *Volcano of the Alban Hills*, edited by R. Trigila, Università degli Studi di Roma "La Sapienza",
1273 Roma, 33-71.
1274
1275 Everdin, J.F., Curtis, G., 1965. The potassium-argon dating of Late Cenozoic rocks in East Africa
1276 and Italy. *Current Anthrop.*, 6, 343-369.
1277
1278 Faccenna, C., Funicello R., Bruni A., Mattei A., Sagnotti L., 1994e. Evolution of a transfer-
1279 related basin: the Ardea Basin (Latium, Central Italy). *Basin Research* 5, 12-11.
1280
1281 Farr, T. G., Hensley, S., Rodriguez, E., Martin, J., Kobrick, M., 2000. The Shuttle Radar
1282 Topography Mission, Proceedings of a Conference held 26-29 October 1999, Toulouse, France.
1283 European Space Agency, 2000. ESA-SP vol. 450, ISBN: 9290926414, p.361.
1284
1285 Ferranti, L., Antonioli, F., Mauz, B., Amorosi, A., Dai Pra, G., Mastronuzzi, G., Monaco, C., Orrù,
1286 P., Pappalardo, M., Radtke, U., Renda, P., Romano, P., Sansò, P., Verrubbi, V., 2006. Markers of
1287 the last interglacial sea-level high stand along the coast of Italy: Tectonic implications.
1288 *Quaternary International* 145/146, 30-54.
1289
1290 Freda, C., Gaeta, M., Palladino, D. M., Trigila, R., 1997. The Villa Senni Eruption (Alban Hills,
1291 Central Italy): the role of H₂O and CO₂ on the magma chamber evolution and on the eruptive
1292 scenario. *Journal of Volcanology and Geothermal Research* 78, 103-120.
1293
1294 Gaeta, M., Freda, C., Marra, F., Arienzo, I., Gozzi, F., Jicha, B., Di Rocco, T., 2016. Paleozoic
1295 metasomatism at the origin of Mediterranean ultrapotassic magmas: constraints inferred
1296 from time-dependent geochemistry of volcanic products from Colli Albani (Central Italy),
1297 *Lithos*, 244, 151-164. <http://dx.doi.org/10.1016/j.lithos.2015.11.034>
1298

1299 Gatta, M., Giaccio, B., Marra, F., Rolfo, M.F., 2017. Trace-element fingerprinting of the 69–36 ka
1300 Colli Albani eruptive units: A preliminary dataset for archaeological and tephra studies in
1301 central-southern Italy. *Journal of Archaeological Science: Reports*, 16, 330-340.
1302

1303 Giaccio, B., Marra, F., Hajdas, I., Karner D.B., Renne, P.R., Sposato A., 2009. $^{40}\text{Ar}/^{39}\text{Ar}$ and ^{14}C
1304 geochronology of the Albano maar deposits: implications for defining the age and eruptive
1305 style of the most recent explosive activity at the Alban Hills Volcanic District, Italy. *Journal of*
1306 *Volcanology and Geothermal Research* 185, 203-213.
1307

1308 Giaccio, B., Niespolo, E., Pereira, A., Nomade, S., Renne, P.R., Alber, P.G., Arienzo, I., Regattieri,
1309 Wagner, B., Zanchetta, G., Gaeta, M., Galli, P., Mannella, G., Peronace, E., Sottili, G., Florindo, F.,
1310 Leicher, N., Marra, F., Tomlinson, E.L., 2017. First integrated tephrochronological record for
1311 the last ~190 kyr from the Fucino Quaternary lacustrine succession, central Italy. *Quaternary*
1312 *Science Reviews* 158, 211-234. <http://dx.doi.org/10.1016/j.quascirev.2017.01.004>
1313

1314 Giordano, G., De Benedetti, A.A., Diana, A., Diano, G., Gaudio, F., Marasco, F., Miceli, M., Mollo,
1315 S., Cas, R.A.F., Funiciello, R., 2006. The Colli Albani mafic caldera (Roma, Italy): stratigraphy,
1316 structure and petrology, *J. Volcanol. Geotherm. Res.*, 155, 49–80.
1317

1318 Grant, K.M., Rohling, E.J., Bronk Ramsey, C., Cheng, H., Edwards, R.L., Florindo, F., Heslop, D.,
1319 Marra, F., Roberts, A.P., Tamisiea, M.E., Williams, F., 2014. Sea-level variability over five glacial
1320 cycles. *Nature Communications* 5, 5076. doi:10.1038/ncomms6076
1321

1322 Jicha, B.R., Singer, B.S., Sobol, P. 2016. Re-evaluation of the ages of $^{40}\text{Ar}/^{39}\text{Ar}$ sanidine
1323 standards and supereruptions in the western U.S. using a Noblesse multi-collector mass
1324 spectrometer. *Chemical Geology* 431, 54–66.
1325

1326 Karner, D.B., Marra, F., 1998. Correlation of fluviodeltaic aggradational sections with glacial
1327 climate history: A revision of the Pleistocene stratigraphy of Rome. *Geological Society of*
1328 *America Bulletin* 110, 748-758.
1329

1330 Karner, D.B., Marra, F., Florindo, F., Boschi, E., 2001a. Pulsed uplift estimated from terrace
1331 elevations in the coast of Rome: Evidence for a new phase of volcanic activity? *Earth and*
1332 *Planetary Science Letters* 188, 135-148.
1333

1334 Karner, D.B., Marra, F., Renne, P.R., 2001b. The history of the Monti Sabatini and Alban Hills
1335 volcanoes: groundwork for assessing volcanic-tectonic hazards for Rome. *J. Volc. and Geoth.*
1336 *Res.* 107: 185-215.
1337

1338 Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed
1339 benthic $\delta^{18}\text{O}$ records. *Paleoceanography* 20, PA1003. doi:10.1029/2004PA001071.
1340

1341 Luberti, G.M., Marra, F., Florindo, F., 2017. A review of the stratigraphy of Rome (Italy)
1342 according to geochronologically and paleomagnetically constrained aggradational
1343 successions, glacio-eustatic forcing and volcano-tectonic processes. *Quaternary International*.
1344 <http://dx.doi.org/10.1016/j.quaint.2017.01.044>
1345

1346 Malinverno, A., Ryan, W.B.F., 1986. Extension in the Tyrrhenian sea and shortening in the
1347 Apennines as results of arc migration driven by sinking of the lithosphere. *Tectonics* 5, 227-
1348 245.

1349
1350 Mariucci, M.T., S. Pierdominici, F. Marra, P. Montone, L. Pizzino, 2008. Looking into a volcanic
1351 area: an overview on the 350m scientific drilling at Colli Albani (Rome, Italy). J. Volcanol.
1352 Geotherm. Res., doi:10.1016/j.jvolgeores.2008.04.007.
1353
1354 Marra, F., Florindo, F., Boschi E., 2008. The history of glacial terminations from the Tiber River
1355 (Rome): insights to glacial forcing mechanisms, *Paleoceanography*, 23, PA2205,
1356 doi:10.1029/2007PA001543.
1357
1358 Marra F., Karner, D.B., Freda, C., Gaeta, M., Renne, P.R., 2009. Large mafic eruptions at the
1359 Alban Hills Volcanic District (Central Italy): chronostratigraphy, petrography and eruptive
1360 behavior. *Journ. of Volc. and Geoth. Res.* 179, 217-232. doi:10.1016/j.jvolgeores.2008.11.009
1361
1362 Marra, F., Sottili, G., Gaeta, M., Giaccio, B., Jicha, B., Masotta, M., Palladino, D.M., Deocampo, D,
1363 2014. Major explosive activity in the Sabatini Volcanic District (central Italy) over the 800-390
1364 ka interval: geochronological - geochemical overview and teprostratigraphic implications,
1365 *Quaternary Science Reviews* 94, 74-101.
1366
1367 Marra, F., Ceruleo, P., Jicha, B., Pandolfi, L. Petronio, Salari, L. , 2015. A new age within MIS 7
1368 for the *Homo neanderthalensis* of Saccopastore in the glacio-eustatically forced sedimentary
1369 successions of the Aniene River Valley, Rome. *Quaternary Science Reviews* 129, 260-274.
1370 doi:10.1016/j.quascirev.2015.10.027
1371
1372 Marra, F., Florindo, F., Anzidei, M., Sepe, V., 2016a. Paleo-surfaces of glacio-eustatically forced
1373 aggradational successions in the coastal area of Rome: assessing interplay between tectonics
1374 and sea-level during the last ten interglacials. *Quaternary Science Review*, 148, 85-100.
1375 <http://dx.doi.org/10.1016/j.quascirev.2016.07.003>
1376
1377 Marra, F., Rohling, E.J., Florindo, F., Jicha, B., Nomade, S., Pereira, A., Renne., P.R., 2016b.
1378 Independent $^{40}\text{Ar}/^{39}\text{Ar}$ and ^{14}C age constraints on the last five glacial terminations from the
1379 aggradational successions of the Tiber River, Rome (Italy). *Earth Planet Sci Lett.* in press.
1380
1381 Marra, F., Gaeta, M., Giaccio, B., Jicha, B., Palladino, D., Polcari, M., Sottili, G., Taddeucci, J.,
1382 Florindo, F., Stramondo, S., 2016c. Assessing the volcanic hazard for Rome: $^{40}\text{Ar}/^{39}\text{Ar}$ and In-
1383 SAR constraints on the most recent eruptive activity and present-day uplift at Colli Albani
1384 Volcanic District, *Geophys. Res. Lett.* 43, 6898-6906. doi:10.1002/2016GL069518.
1385
1386 Marra, F., Florindo, F., Petronio, C., 2017. Quaternary fluvial terraces of the Tiber Valley:
1387 geochronologic and geometric constraints on the back-arc magmatism-related uplift in central
1388 Italy. *Journal Scientific Reports* 7: 2517. DOI:10.1038/s41598-017-02437-1
1389
1390 Marra, F., Petronio, C., Salari, L., Florindo, F., Giaccio, B., Sottili, G., 2018a. A review of the
1391 Villafranchian fossiliferous sites of Latium in the framework of the geodynamic setting and
1392 paleogeographic evolution of the Tyrrhenian Sea margin of central Italy, *Quaternary Science*
1393 *Reviews* 191, 299-317. 10. 1016/ j. quascirev. 2018. 05. 011
1394
1395 Marra, F., Petronio, C., Ceruleo, P., Di Stefano, G., Florindo, F., Gatta, M., La Rosa, M., Rolfo, M.F.,
1396 Salari, L., 2018b. The archaeological ensemble from Campoverde (Agro Pontino, central Italy):
1397 new constraints on the Last Interglacial sea level markers. *Scientific Reports*, SREP-18-23649,
1398 DOI : 10.1038/s41598-018-36111-x

1399
1400 Marra F., Nomade S., Pereira A., Petronio C., Salari L., Sottili G., Bahain J.J., Boschian G., Di
1401 Stefano G., Falgueres C., Florindo F., Gaeta M. Giaccio B., Masotta M., 2018c. A review of the
1402 geologic sections and the faunal assemblages of Aurelian Mammal Age of Latium (Italy) in the
1403 light of a new chronostratigraphic framework. *Quaternary Science Reviews* 181, 173-199.
1404 doi.org/10.1016/j.quascirev.2017.12.007
1405
1406 Marra, F., Bahain, J.-J., Jicha, B., Nomade, S., Palladino, D.M., Pereira, A., Tolomei, C., Voinchet,
1407 P., Anzidei, M., Aureli, D., Ceruleo, P., Falguères, C., Florindo, F., Gatta, M., Ghaleb, B., La Rosa,
1408 M., Peretto, C., Petronio, C., Rocca, R., Rolfo, M.F., Salari, L., Smedile, A., Tombret, O., 2019a.
1409 Reconstruction of the MIS 5.5, 5.3 and 5.1 coastal terraces in Latium (central Italy): a re-
1410 evaluation of the sea-level history in the Mediterranean Sea during the Last Interglacial,
1411 *Quaternary International*.
1412
1413 Marra, F., Florindo, F., Jicha, B.R., Nomade, S., Palladino, D.M., Pereira, A., Sottili, G., Tolomei, C.,
1414 2019b. Assessing volcano-tectonic hazard of the Monti Sabatini Volcanic District on the city of
1415 Rome (central Italy): evidence from new geochronologic constraints on the Tiber River MIS 5
1416 terraces, *Scientific Reports*, in press.
1417
1418 Masotta, M., Gaeta, M., Gozzi, F., Marra, F., Palladino, D.M., Sottili, G., 2010. H₂O- and
1419 temperature-zoning in magma chambers: the example of the Tufo Giallo della Via Tiberina
1420 eruptions (Sabatini Volcanic District, central Italy). *Lithos* 118, 119-130.
1421
1422 Nicoletti, M., 1969. Datazioni argon-potassio di alcune vulcaniti delle regioni vulcaniche
1423 Cimina e Vicana. *Per. Mineral.*, 38, 1-20.
1424
1425 Nisi, M.F., Antonioli, F., Dai Pra, G., Leoni, G., Silenzi S., 2003. Coastal Deformation between the
1426 Versilia and the Garigliano plains (Italy) derived from the elevations of the Last Interglacial
1427 stage, *Journal of Quaternary Science* 18, 709-721.
1428
1429 Palladino, D., Simej, S., Sottili, G., and Trigila, R., 2010, Integrated approach for the
1430 reconstruction of stratigraphy and geology of Quaternary volcanic terrains: An application to
1431 the Vulsini Volcanoes (central Italy), in *Stratigraphy and Geology of Volcanic Areas* (eds. G.
1432 Groppelli, and L. Viereck-Goette), *The Geological Society of America Special Paper*, 464, 63-84.
1433 doi: 10.1130/2010.2464(04).
1434
1435 Patacca, E., Sartori, R., Scandone, P., 1990. Tyrrhenian basin and apenninic arcs: kinematic
1436 relations since late Tortonian times. *Mem. Soc. Geol. It.* 45, 425-451.
1437
1438 Peccerillo, A., Frezzotti, M.L., 2015. Magmatism, mantle evolution and geodynamics at the
1439 converging plate margins of Italy. *Journal of the Geological Society*.
1440 <http://dx.doi.org/10.1144/jgs2014-085>
1441
1442 Pereira, A., Nomade, S., Falguères, C., Bahain, J.-J., Tombret, O., Garcia, T., Voinchet, P.,
1443 Bulgarelli, A.G., Anzidei, P., 2017. 40Ar/39Ar and ESR/U- series data for the La Polledrara di
1444 Cecanibbio archaeological site (Lazio, Italy). *Journal of Archaeological Science: Reports*, in
1445 press.
1446

1447 Perini, G., Francalanci, L., Davidson, J.P., and Conticelli, S., 2004, Evolution and genesis of
1448 magmas from Vico volcano, Central Italy: multiple differentiation pathways and variable
1449 parental magmas, *Journal of Petrology*, **45**, 139–182.
1450
1451 Rivera, T.A., Storey, M., Schmitz, M.D., Crowley, J.L., 2013. Age intercalibration of $^{40}\text{Ar}/^{39}\text{Ar}$
1452 sanidine and chemically distinct U/Pb zircon populations from the Alder Creek Rhyolite
1453 Quaternary geochronology standard. *Chemical Geology* 345, 87-98.
1454
1455 Rohling E.J., Grant, K., Bolshaw, M., Roberts, A.P., Siddall, M. Hemleben, Ch., Kucera, M., 2009.
1456 Antarctic temperature and global sea level closely coupled over the past five glacial cycles.
1457 *Nature Geoscience* 2, 500-504. DOI: 10.1038/NGEO557
1458
1459 Serri, G., Innocenti, F., Manetti, P, 1993. Geochemical and Petrological evidence of the
1460 subduction of delaminated Adriatic continental lithosphere in the genesis of the Neogene-
1461 Quaternary magmatism of Central Italy, *Tectonophysics* 223, 117-147.
1462
1463 Sevink, J., Di Vito, M.A., Piochi, M., Mormone, A., Van Gorp, V., Bakels, C., 2018. A rare Mid-
1464 Würmian lithoid tuff in the Agro Pontino graben (Southern Lazio, Italy) and its identification
1465 as an Albano 5-7 related distal tephra deposit (41-36 kaBP): characteristics, provenance and
1466 palaeogeographical implications. *Annals of Geophysics*, 61, 1, S109. DOI: 10.4401/ag-7534
1467
1468 Sottili, G., Palladino, D.M., Marra, F., Jicha, B., Karner, D.B., Renne, P., 2010. Geochronology of
1469 the most recent activity in the Sabatini Volcanic District, Roman Province, central Italy, *Journ.*
1470 *of Volc. and Geoth. Res.* 196, 20-30. DOI:10.1016/j.jvolgeores.2010.07.003
1471
1472 Sottili G., Palladino D.M., Zanon V., 2004. Plinian activity during the early eruptive history of
1473 the Sabatini Volcanic District, Central Italy. *J. Volcanol. Geotherm. Res.* 135, 361-379.
1474
1475 Villa, P., Pollarolo, L., Conforti, I., Marra, F., Biagioni, C., Degano, I., Lucejko, J.J., Tozzi, C.,
1476 Pennacchioni, M., Zanchetta, G., Nicosia, C., Panzeri, L., Martini, M., Sibilila, E., From Neandertals
1477 to modern humans: New data on the Uluzzian. *Plos One* 13(5): e0196786.
1478 <https://doi.org/10.1371/journal.pone.0196786>
1479
1480

MIS 9 to MIS 5 terraces along the Tyrrhenian Sea coast of Latium (central Italy): assessing interplay between sea-level oscillations and tectonic movements

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Abstract

We present a review of the geomorphology of the Tyrrhenian Sea coast of central Italy integrated by a novel structural-geomorphological study coupled with statistical analysis of topographic culminations and comparison with a Digital Elevation Model, aimed at reconstructing a suite of paleo-surfaces corresponding to remnant portions of marine terraces. We performed geochronological, sedimentological, micromorphological and mineralogical investigations on the deposits forming the different paleo-surfaces between Civitavecchia and Anzio town, in order to provide chronostratigraphical, paleogeographical and paleoenvironmental constraints. Using the newly achieved dataset we correlate these paleo-surfaces with the coastal terraces formed during past sea-level highstands, as recognized by previous studies, and we refine their correlation with the Marine Isotope Stage (MIS) timescale.

In particular, we have extended our geomorphological analyses landward in the area between the Tiber River mouth and Anzio, in order to include the oldest paleo-surface developed above the deposits of the last large explosive eruption at 365 ± 4 ka in the Colli Albani Volcanic District. Results of this study allow us to recognize a set of higher paleo-surfaces at elevation ranging 108 to 71 m a.s.l., which we interpret as one tectonically displaced, widespread coastal terrace originated during the MIS 9.1 highstand. We correlate the previously identified paleo-surfaces of 66-62 m and 56-52 m with the equivalent coastal terraces developed during the sea-level highstands of sub-stages 7.5 and 7.3/7.1. Moreover, based on data from literature on relative elevation of maximum sea level during the highstands of MIS 11 through

MIS 5.1, we assess the regional uplift and the concurrent tectonic displacements that have occurred since 900 ka in this area.

Keywords: paleo-surface; coastal terrace; glacio-eustasy; regional uplift

Highlights:

We reconstruct a suite of six paleo-surfaces along the central Tyrrhenian Sea coast
Paleoenvironmental data identify these paleo-surfaces as remnants of coastal terraces
We provide $^{40}\text{Ar}/^{39}\text{Ar}$ age constraints to the terraced sedimentary deposits
We correlate these terraces with the Marine Isotope Stage record
We identify previously unrecognized MIS 9 sea-level markers in this region
We assess regional uplift and tectonic displacements in the last 400 ka

1. Introduction

The Tyrrhenian Sea coast of Latium (Figure 1) is part of a geodynamic domain characterized by back-arc extensional processes (Malinverno and Tayan, 1986; Patacca et al., 1990) that during Pleistocene times have led to the formation of an ultra-potassic chain of volcanic districts (Serri et al., 1993; Conticelli and Peccerillo, 1992; Peccerillo and Frezzotti, 2015). Concurrent with the volcanic processes, regional uplift has caused the progressive emergence of this area since the end of the Santernian (lower Calabrian), around 1.5 Ma, leading to widespread continentalization since ~1 Ma (Barberi et al., 1994; Marra et al., 2018a). The regional uplift along the Tyrrhenian coast of Latium has been interpreted as driven by the subduction process and uprising of metasomatized magma bodies on the Tyrrhenian Sea Margin of central Italy, superimposed on a smaller isostatic component of uplift (Marra et al., 2017, and references therein). Two major pulses of uplift are recognized: 0.86 through 0.5 Ma, and 0.25 Ma through the Present (Marra et al., 2016a); as a result of this overall uplifting regime, the continental, fluvial-lacustrine and coastal deposits in this area formed a widespread pattern of terraces that, similar to other regions in the world (e.g., Bridgland and Westaway, 2008), are organized in a staircase geometry, with the oldest surfaces at highest elevation.

Geographic extension and rates of the most recent phases of this uplift during Middle-Late Pleistocene have been assessed by a series of studies reconstructing a suite of coastal terraces and correlating them with the sea-level highstands identified by the Marine Isotope Stage (MIS) record (e.g., Karner et al., 2001a; Nisi et al., 2003; Ferranti et al., 2006). More recently, a re-evaluation of the geometry and the age of these terraces in the coastal area between the Argentario and Anzio promontories has been proposed by means of an original geomorphological approach and the integration of new geochronologic constraints provided by $^{40}\text{Ar}/^{39}\text{Ar}$ ages of volcanic layers intercalated within the glacio-eustatically forced aggradational successions forming the terraced deposits in this region (Marra et al., 2015; 2016a). Moreover, a new geomorphologic study coupled with biochronologic constraints allowed Marra et al. (2018b, 2019a) to extend the reconstruction of a complete suite of terraces in the coastal reach between Anzio and Circeo promontories, and to propose their correlation with MIS 7.5 through MIS 5.1. In contrast, only a poorly defined paleo-surface ranging 61-67 m a.s.l. has been dubiously assigned to the MIS 9 terrace (Marra et al., 2016a). Moreover, geochronologic constraints so far provided to the local MIS 9 aggradational succession (Aurelia Formation, Karner and Marra, 1998) evidenced a remarkable anomaly, significantly pre-dating glacial termination IV and the completion of MIS 9 highstand (Marra

et al., 2016b). Therefore, assessing the geometry and providing time constraint on the deposits of the MIS 9 coastal terrace in this region may have notable implications for understanding the response to the global paleo-climatic signal and on the tectonic process acting on the Tyrrhenian Sea margin of central Italy.

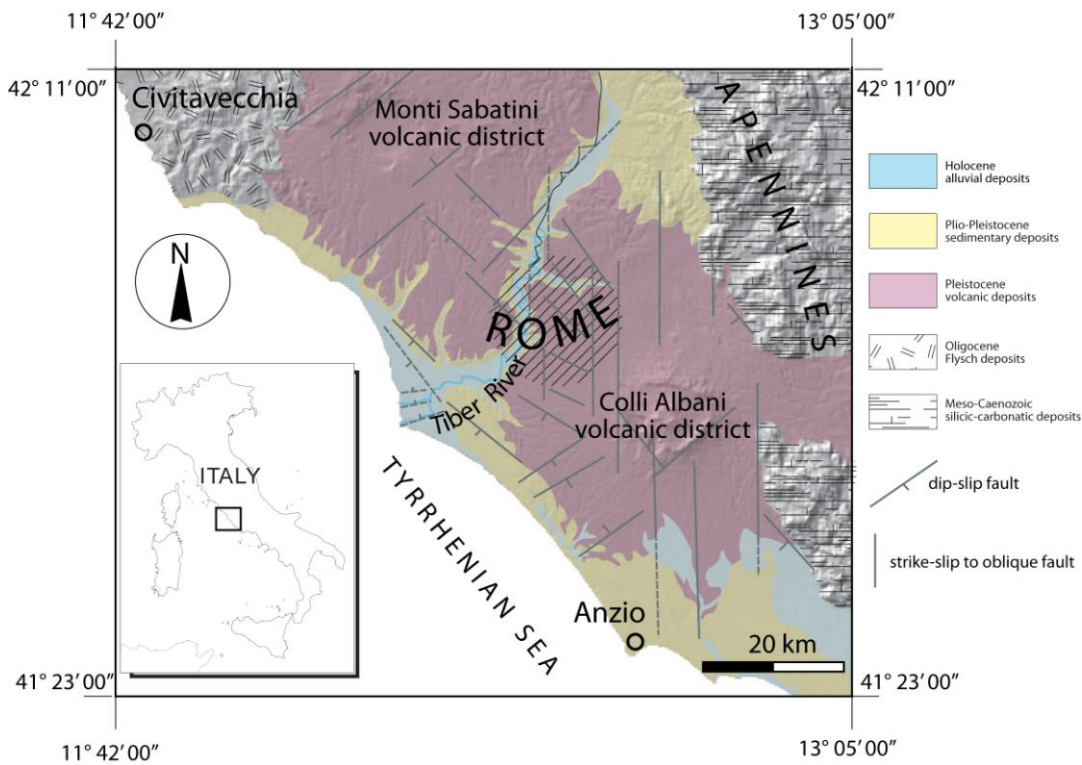


Figure 1 - DEM image of the Tyrrhenian Sea margin of central Italy showing the main structural features of the investigated area (after Acocella and Funicello, 2006; Frepoli et al., 2010).

In the present paper we have refined the structural-geomorphological study in the previously investigated sector comprised between Civitavecchia and Anzio, and we have re-assessed the statistical analysis of the elevations of the paleo-surfaces correlated by Marra et al. (2016a, 2019a) with the MISs. In particular, we have extended the geomorphological analysis landward, in order to include the oldest paleo-surface affecting the deposits of the last large eruption in the Colli Albani Volcanic District (Villa Senni Eruption Cycle, 365 ± 4 ka, Marra et al., 2009) in the area between the Tiber mouth and Anzio. Two huge pyroclastic-flow deposits emplaced during this eruption phase (Tufo Lionato and Pozzolanelle, Freda et al., 1995) mantle the surface with a volcanic cover spreading radially as far as 50 km from the vent and reaching up to 20 m in thickness, locally (De Rita et al., 1995; Giordano et al., 2006; Mariucci

et al., 2008). Due to this pyroclastic cover, the paleo-surfaces older than 365 ka are completely buried and no geomorphologic evidence is expected for them in this area.

We performed chronostratigraphical, sedimentological, micromorphological, mineralogical and petrographic investigations of the deposits forming the different paleo-surfaces in order to provide geochronological, paleogeographical and paleoenvironmental constraints. We used four $^{40}\text{Ar}/^{39}\text{Ar}$ age determinations on detrital sanidine crystals extracted from key deposits in order to provide post-*quem* ages on the paleo-surfaces and relative chronologic constraints for their correlation with the suite of coastal terraces recognized and geochronologically constrained by previous studies, refining their correlation with the MIS timescale.

2. Geological Setting

The study area is located on the Tyrrhenian Sea margin of central Italy (Figure 1).

Since the Middle Pleistocene the interplay between glacio-eustatic sea-level variations, tectonic processes, sedimentation and volcanic activity has built the geological framework of this area (Luberti et al., 2017, and references therein). During periods of sea-level fall, erosion occurred, whereas deposition took place during phases of sea-level rise, filling previously excavated incisions with a suite of aggradational successions (Karner and Marra, 1998; Marra et al., 2008). A thick succession of pyroclastic-flow deposits, from both the Colli Albani and Monti Sabatini volcanic districts, and subordinated Sabatinian air-fall deposits, interfingers with the continental sediments. After the last volcanic eruptions at 36 ka (Marra et al., 2016c), the volcanic plateau was deeply incised during the Last Glacial, partly as a consequence of the intervening regional uplift (Marra et al., 2016a). Eventually, the paleovalleys were filled by fluvial deposits as a consequence of the sea-level rise after the last glacial termination.

3. Methods

3.1 Geomorphological analysis

In the present study, paleo-surfaces have been mapped following the geomorphological approach described in Marra et al. (2016a; 2017), based on the identification of a set of flat surfaces characterized by topographic culminations with elevation ranging through a few meters around a mean value. Selected topographic culminations of the reconstructed paleo-surfaces were detected on Istituto Geografico Militare 1:25.000 topographic maps of Italy. They include all the hilltops (i.e., each elevation point within a closed, 5 m interval contour line, represented by upward triangles in the figures of this work) and other quasi-equivalent points within plateau-like sectors (downward triangles). The identification of the paleo-

surfaces is based on a combined approach that integrates statistically significant concentrations of elevations around a mean value, and the morphologic evidence for the concentration of these elevation points within a finite area, as detected in the maps (see Marra et al., 2016a for detailed methodology). The full dataset of topographic elevations is reported on the scanned 1:25.000 topographic maps and provided as Supplementary Material #1.

Distribution of the topographic culminations has been statistically analyzed in order to verify the occurrence of discrete elevation intervals corresponding to peaks of concentration, which can be assumed to be the mean level for each paleo-surface. Comparison between the complete dataset of elevation points (hilltops + plateaux) and that represented only by hilltop elevations has been also provided, to highlight possible subjective selection of the plateau-like culminations and to exclude biases.

Finally, a set of elevation ranges defining the principal paleo-surfaces identified using the described geomorphological method has been mapped through DEM analyses, to compare the results.

3.2 DEM analysis

Five classes of elevations highlighted by the geomorphological study have been mapped using an interferometric Digital Elevation Model (DEM) with a ground resolution of 30 meters (1 arcsec) derived from the NASA SRTM mission (<http://www2.jpl.nasa.gov/srtm>, Farr et al., 2000). When the overall topographic relief of the Italian peninsula is considered, the DEM shows an averaged altitude accuracy of ~15 meters, but in our case, considering areas quite close to the sea and showing low altitude ranges (i.e., 0 - 120 m), the accuracy is one order of magnitude better, and can be estimated in 1-2 m.

The analysis was performed entirely within a GIS environment. Initially, the DEM was delimited on the basis of the study area using a polygon shapefile, then the various classes were identified one by one, generating 5 different layers. Five queries were applied to the DEM, each time considering the maximum and minimum values of each class so as to isolate the desired altitude interval. Finally, the layers were merged into a single one and symbolized with 5 different colors, one for each class.

3.3 Micromorphological analyses

Three undisturbed soil samples (TML-CC, VDT, VOC) and three loose sand samples (TML-SA, PC-SA, CSR-SA) have been studied in thin sections for micromorphological analysis and for

sand mineralogy determination, respectively, aimed at investigating the pedological and/or sedimentological features, and to recognize the origin of the deposit forming the corresponding paleo-surface. One sediment sample collected from the paleo-surface ranging 60-67 m (CR1) in the northern sector was analyzed by Villa et al. (2018), and the results are reported here to integrate with the dataset above.

Descriptions of thin sections are summarized in Table 1, results of the petrographic determination of sand grains are reported in Table 2. Methods and microphotographs of thin sections for micromorphological analyses are provided in Supplementary File #2A.

3.4 Mineralogical analyses

Fifteen samples collected close to the top, and in some instances at increasing depth, on the different paleo-surfaces (VL-1, VL-2, MM, VCR-1, VCR-2, VCR-3, TB-1, TB-2, TB-3, VVL, TML-SA, TRIG, VDT, SPR, RUT), and three sediment samples (RSC, CDC, CR-1), have been analyzed by X-rays diffraction and with a scanning electron microprobe (SEM) in order to describe their mineralogy and texture.

Methods, microphotographs and full-resolution diffractograms are provided in Supplementary File #2B-C.

3.5 $^{40}\text{Ar}/^{39}\text{Ar}$ dating

Sanidine crystals were extracted from four samples of sediment to provide terminus post-quem ages to the time of deposition of the terrains and/or the accretionary soils forming the paleo-surfaces ranging 98-108 m (TML-SA), 71-79 m (RSC-SA), 60-67 m (CR-3), 51-57 m (CSR-SA) a.s.l., in the area between the Tiber mouth and Anzio. Sampling locations are shown in Figure 3.

Sanidine phenocrysts were co-irradiated with the 1.1864 Ma Alder Creek sanidine standard (Jicha et al., 2016; Rivera et al., 2013) at the Oregon State University TRIGA reactor in the Cadmium-Lined In-Core Irradiation Tube. Single crystal fusion analyses were performed at the WiscAr laboratory at the University of Wisconsin-Madison using a 60W CO₂ laser and a Noblesse multi-collector mass spectrometer following Jicha et al. (2016). Results are reported in Table 4. Full analytical data are reported in Supplementary Material #3.

4. Results

4.1 Geomorphological analysis

Results of the geomorphological study performed for the present work in the coastal area between Civitavecchia and Anzio are in good agreement with those previously obtained by Marra et al. (2016a, 2019a). We have statistically re-analyzed hilltops and plateaux elevations separately, in the two coastal sectors north and south of the Tiber mouth. Very similar statistical assessment for the elevation ranges of the detected paleo-surfaces have been obtained for the two sectors, which are reported in Figure 2 and 3, respectively. In these figures, all the topographic culminations identified on the 1:25.000 maps are indicated with triangles of different colors. In the northern sector, each color is associated with an elevation range defining a paleo-surface which, in turn, is established from the statistical analysis. Elevation ranges for the paleo-surfaces are represented by grey boxes of cumulative frequency above a threshold value of $n=2$ for a total number of data >20 (red horizontal line in Figure 2b), while continuous distributions are considered for classes of $n < 20$. Open triangles are used for hilltops whose elevation is not statistically significant and are not associated with a paleo-surface. These elevations are interpreted as reflecting topographic culminations that represent eroded higher rank paleo-surfaces; for this reason, the same color used for the corresponding pristine paleo-surface is also used for these triangles.

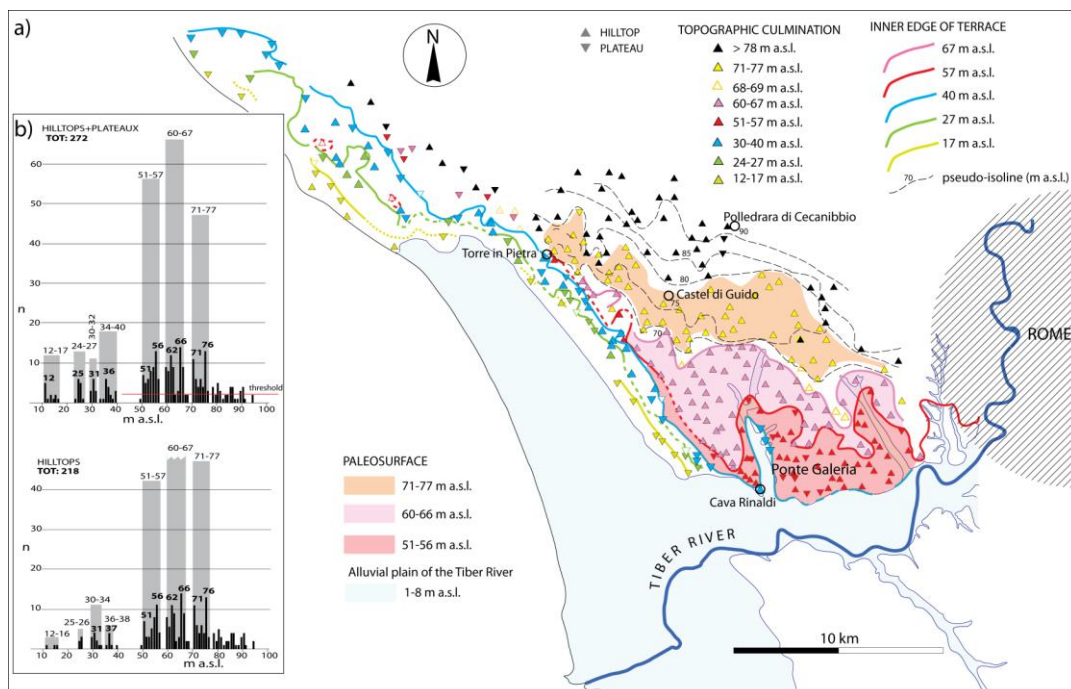


Figure 2 - Geomorphological map (a) and topographic culmination statistics (b) in the northern sector between Civitavecchia and the Tiber mouth. Elevations of topographic culmination are omitted for clarity in this figure and can be found in Suppl. Mat. #1A. See text for comments.

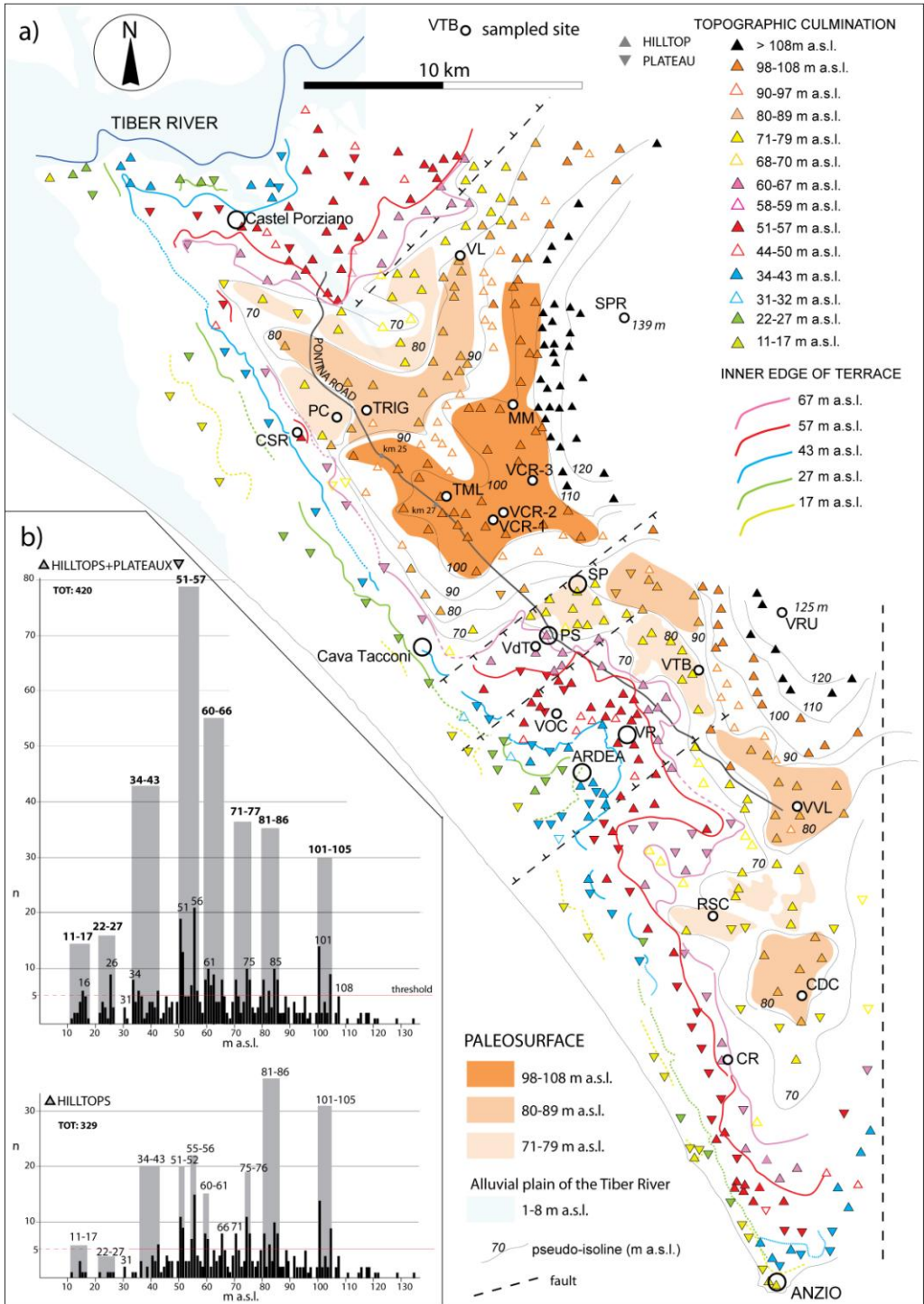


Figure 3 - Geomorphological map (a) and topographic culmination statistics (b) in the southern sector between the Tiber mouth and the Anzio promontory. Elevations of topographic culmination are omitted for clarity in this figure and can be found in Suppl. Mat. #3. See text for comments.

A similar approach is used in the southern sector where, due to the larger number of data, a threshold value of $n=5$ is established to define the classes of elevation for all the paleo-surfaces except the lowest two (Figure 3b). Moreover, in a few cases the elevation range for each color is slightly larger than the mean elevation range (grey boxes) established for the paleo-surfaces based on histograms, in order to include all topographic points.

Color shading is used in Figure 2 for three oldest paleo-surfaces which have a wider extent and are located inland, while inner margins are represented by solid colored lines for the paleo-surfaces stretching along the coast, which are assumed to represent coastal terraces. Different shades of the orange color are used in Figure 3 to highlight the highest paleo-surfaces that are located inland which, according to discussion in the following sections, are interpreted as having the same age, whereas inner terrace margins are reported for the youngest paleo-surfaces along the coast.

In both sectors illustrated in Figures 2 and 3, three lowest orders of terrace are identified by a series of topographic culminations, each one providing well-clustered, distinct elevation ranges, which define three paleo-surfaces narrowly elongated parallel to the coast. The lowest paleo-surface ranges 12-17 m a.s.l., with a peak at 12 m (Figure 2b), and 12-18 m a.s.l., with a peak at 16 m (Figure 3b), in the northern and in the southern sector, respectively. A second paleo-surface has very narrow ranges of 24-27 and 22-27 m a.s.l., with peaks at 25 and 26 m, in the northern and in the southern sector, respectively.

A third, higher paleo-surface is characterized by a wider range of elevations, with a main concentrations between 34-40 and 34-43 m a.s.l. in the northern and southern sector, respectively, and with a minor peak at 31 m, in both sectors.

A fourth, wide paleo-surface is that ranging 51-57 m a.s.l. and characterized by two relative maxima at 51 and 56 m, in both sectors. Another two well-defined elevation ranges of 60-67 m, and of 71-77 m, are clearly identified in both sectors, and are associated with fifth and sixth paleo-surfaces, respectively.

Finally, two more concentrations of elevation values, peaking at 80-86 and 101-105 m a.s.l., define the two highest paleo-surfaces on the inland coastal sector south of the Tiber mouth, whereas in the northern sector topographic culminations show progressively increasing elevation inland, without any apparent clustering around a mean value.

Comparison of the results of the geomorphological study with the DEM of Figure 4 shows a very satisfactory match. In particular, we note the close correspondence between the geometrical patterns defined by the 51-57 m paleo-surface in the geomorphological maps of Figure 2 and 3, and in the DEM image of Figure 4 (represented by the red color in both representations), as well as, between those pertaining to the highest paleo-surface of 98-108 m (represented by the deep orange color in Figure 3 and by the deep blue color in Figure 4).

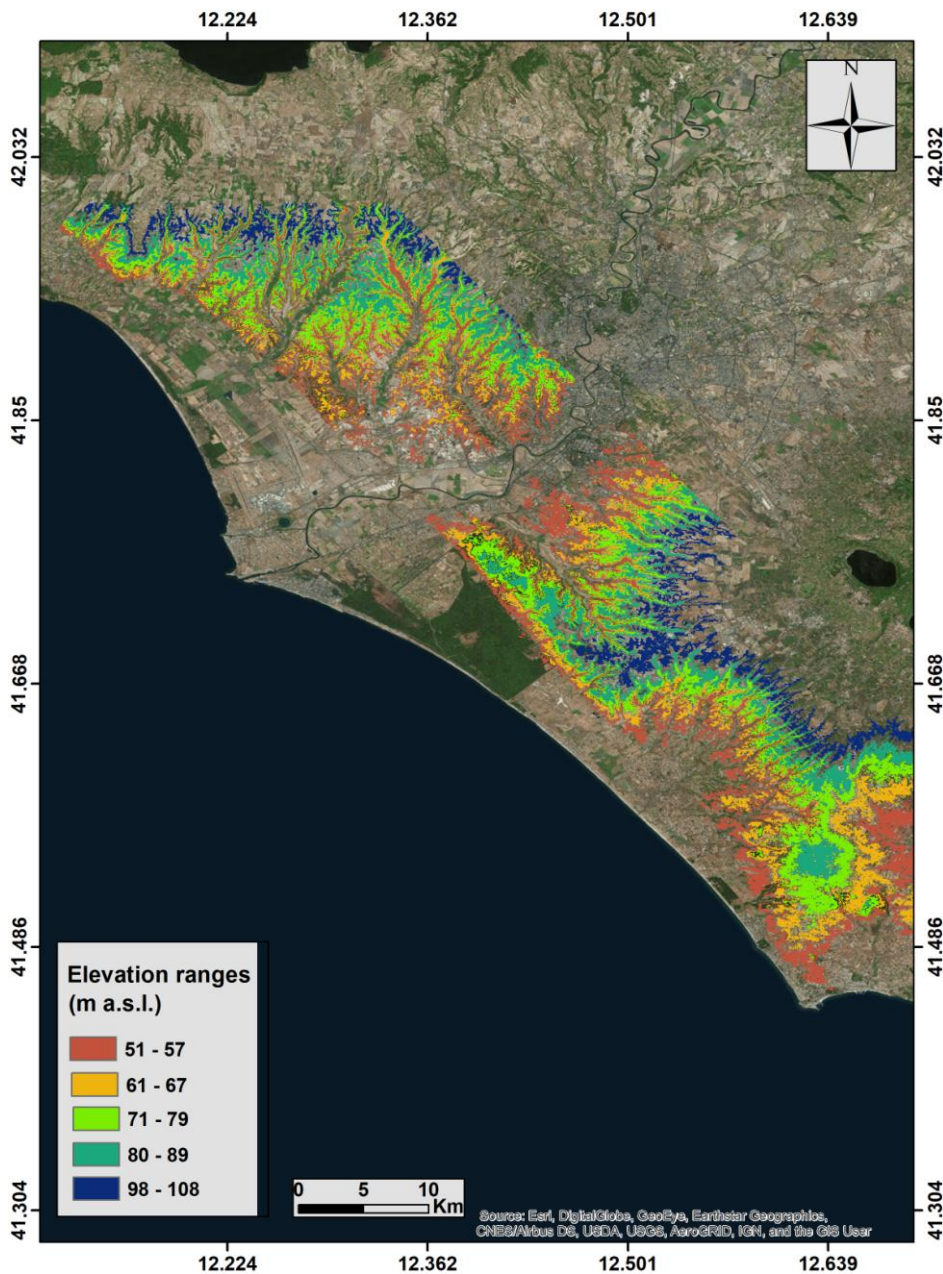


Figure 4 - Interferometric Digital Elevation Model (DEM) mapping of the five classes of elevations highlighted by the geomorphological study.

4.2 Stratigraphic investigations

4.2.1 Paleo-surface 98-108 m a.s.l.

Exposure of the sedimentary deposits forming the highest paleo-surface in the investigated area is provided by a road cut in Tenuta Monti di Leva (TML), at km 27 of Via Pontina (Figure 5a, see Figure 3 for location). Here, a pedogenically modified horizon occurs in the upper 100 cm and is constituted by fine to medium sized sand in silty-clayey matrix, orange in color (Figure 5a-a"). A 180 cm thick concretionary layer, constituted by aggregated, cm-sized Fe and Mn nodules within a sand matrix, occurs at the bottom of this horizon and overlies a red paleosol developed on top of the pyroclastic-flow deposit of Pozzolanelle (Villa Senni Eruption Cycle, 365 ± 4 ka; Freda et al., 1997; Marra et al., 2009). A sample of the upper sand layer (TML-SA) and another from the concretionary layer (TML-CC) were analyzed for mineralogy and micromorphology, respectively. Forty-one sanidine crystals extracted from sample TML-SA were dated by the $^{40}\text{Ar}/^{39}\text{Ar}$ method.

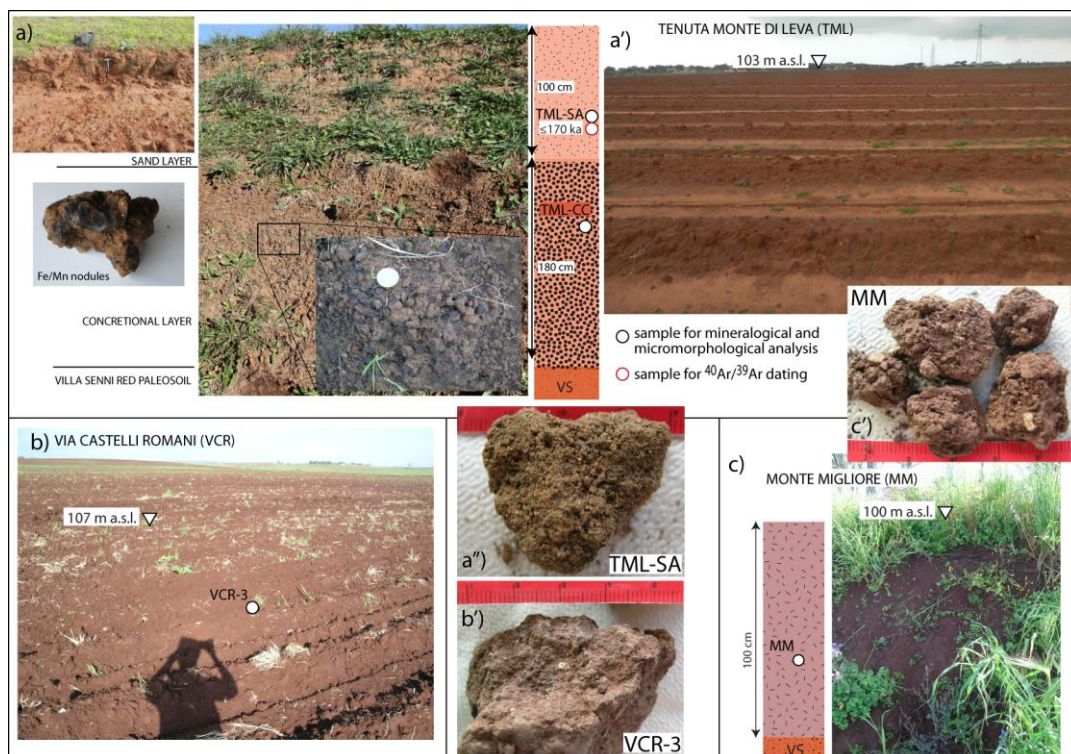


Figure 5 - Photographs and stratigraphic schemes showing the 98-108 m a.s.l. paleo-surface and the sections from which samples analyzed in the present study were collected. See text for comments.

The Tenuta Monte di Leva paleo-surface is affected by intensive ploughing which exposes shreds of the upper, orange sand layer, allowing recognition of the presence of this sedimentary deposit throughout the sector crossed by the Pontina Road between km 27 and km 25 (see Figure 3a). A similar in color, but finer sandy-clay deposit is exposed by plowing grooves on top of this highest paleo-surface, further inland. Four samples were collected along the Via dei Castelli Romani and Via Laurentina, at increasing distance inland, with respect to the Tenuta Monte di Leva site (Figure 3). Three samples (VCR 1-3) were collected at elevations between 105 and 107 m a.s.l. in the fields exposing clods of the sub soil (Figure 5b). Although the direct contact is not exposed in this flat sector, a geologic substrate represented by the Pozzolanelle pyroclastic-flow deposit (hereby PL) is visible in the scanty outcrops along the stream incisions at its margin. A fourth sample (MM) was collected at the Monte Migliore-La Selvotta locality, at 100 m a.s.l., from the middle of a 100 cm thick, dark red paleosol developed above the PL, exposed by a road cut (Figure 4c). A larger amount of clay matrix, dark red in color, characterizes the samples collected in these inland sectors of the 98-108 paleo-surface (VCR 1, 2, 3, MM, Figure 5b'-c'). Frequent pyroxene crystals and sparse, altered volcanic scoriae 1 to 5 mm in size, are embedded in the clay matrix of these soils, evidencing an at least partial origin from the directly underlying volcanic deposit. Two more samples were collected in a later time at higher elevation, in the area inland with respect to that pertaining to the 98-108 paleosurface (SPR at 139 m a.s.l.) and with respect to the narrow alignment of topographic culminations ranging 100-110 m in the more southern sector (RUT at 125 m a.s.l.) (Figure 3), aimed at investigating the origin of the abundant silico-clastic fraction highlighted by micromorphologic and petrographic analyses in the soils developed above the volcanic substrate.

4.2.2 Paleo-surface 80-89 m a.s.l.

Different fragments of this paleo-surface are identified northwest and southeast of the highest sector corresponding to the 98-108 paleo-surface (Figure 3). As for the latter, the 80-89 paleo-surface is also developed above different geologic substrates as a function of the distance from the coastline: above the PL in the inland sectors, and above sedimentary sand deposits to the southwest. Five samples were collected in the different sectors of this paleo-surface. Two samples (VL-1, VL-2, Figure 6a) were collected in the middle and at the surface

of a thick paleosol developed above the PL in Via Laurentina, in the inland margin of the northernmost stretch of this paleo-surface. A further sample (TRIG, Figure 6b) was collected at its opposite, seaward extreme, on the ground surface in a sandy deposit (Figure 3).

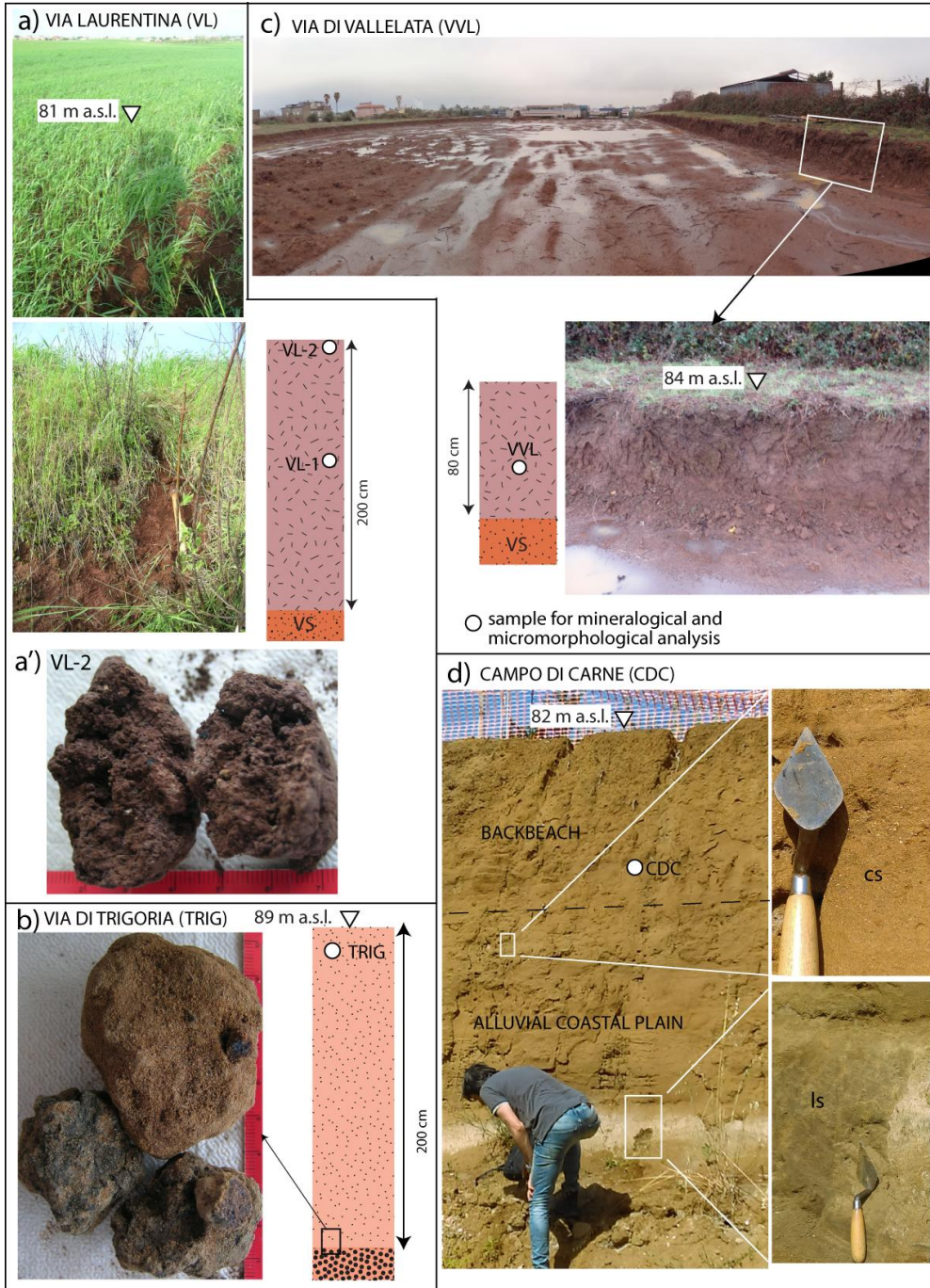


Figure 6 - Photographs and stratigraphic schemes showing the 80-89 m a.s.l. paleo-surface and the sections from which samples analyzed in the present study were collected. See text for comments.

This sedimentary deposit is quite similar to that cropping out in Tenuta Monte di Leva (TML): it is a medium-to-fine grained, orange sand in a sparse clay matrix, without sedimentary structures, ca. 3 m thick (Figure 6b). At the base of the exposed section a concretionary layer rich in Mn/Fe nodules, quite similar to that occurring in TML, is present.

A fourth sample (VVL, Figure 6c) was collected in the middle of an ca. 80 cm thick paleosol developed above the PL in Via Vallelata, in the inland margin of the southernmost stretch of the 80-89 m paleo-surface (Figure 3). This reddish soil, like the thicker soil sampled in Via Laurentina (Figure 6a'), consists of very fine, clayey sediment containing abundant pyroxene crystals and altered volcanic scoriae, and appears quite similar to the other soils developed directly above the PL sampled for this study.

Finally, one sample (CDC) was collected in Campo di Carne in a road excavation exposing a ca. 3 m thick deposit consisting of fine, faintly bedded sand in a sparse clay matrix, with dm-thick layers of coarse sand (cs in Figure 6d), whose top at 82 m a.s.l. is part of the seaward portion of the 80-89 m a.s.l. paleo-surface. A layer of dark, greenish loamy fine sand, ca. 60 cm thick, occurs at the base of the exposed section in CDC (ls in Figure 6d).

4.2.3 Paleo-surface 71-79 m a.s.l.

Two particularly level, small sectors at elevations around 76 m a.s.l. can be detected in the northern and southern margins of the investigated area, in the Podere Carafa (PC) and Riserva Carpineto (RSC) estates (Figure 3). In the PC, an almost perfectly flat area (Figure 7a) is truncated by a sharp scarp to the southwest, dividing it from another level area at ca. 56 m a.s.l. (Castel Romano -CSR), while it connects more gently to a slightly higher sector, corresponding to the 80-89 paleo-surface, to the northeast. A marked fluvial incision dissecting the plateau exposes the terrains forming the 71-79 m paleo-surface, showing massive sand deposit of at least five meters thickness, where sample PC-SA analyzed during this study was collected (Figure 7a).

A remarkably similar geomorphologic and stratigraphic setting is observed at the RSC. Here a wide level area at elevations ranging 70-79 m is intensely dissected by steep stream valleys, and almost without geomorphologic break connects with another large area to the southeast, including the Campo di Carne (CDC) site, at an elevation between 80 and 85 m a.s.l. (Figure 3). A massive, medium to coarse sand deposit with sparse, well-rounded fine gravel (sample RSC,

Figure 7b) constitutes the geologic substrate in this area, and directly overlies the lower flow unit of the Villa Senni eruption cycle (Tufo Lionato).



Figure 7 - Photographs and stratigraphic schemes showing the 71-79 m a.s.l. paleo-surface and the sections from which samples analyzed in the present study were collected. See text for comments.

A portion of this 71-79 m a.s.l. paleo-surface also occurs within the structurally controlled sector of Ardea, bordered by the NE-SW trending normal faults of the Ardea Basin (Figure 3). This is a half-graben which originated as a transversal Tyrrhenian Sea basin in Lower Pleistocene times, as evidenced by off-shore seismic lines (Faccenna et al., 1994). The continued Middle Pleistocene activity of these faults is suggested by the marked control on the paleo-coastlines, testified by the geometry of the inner edges of the MIS 7 and MIS 5 terraces reconstructed in Marra et al. (2016a, 2019a) and shown by our refined study in Figure 3 and in Figure 4.

In contrast to the more seaward sectors, here the 71-79 paleo-surface is developed upon the PL (Figure 7c-d), and characterized by a shallow, 60-80 cm thick, dark brown paleosol. Three samples have been vertically sampled in this paleosol at the Via di Torre Bruna (VTB 1-3, Figure 7c).

Figure 2 shows a wide 71-77 m paleo-surface that we have reconstructed in the coastal sector north of the Tiber mouth (Ponte Galeria area), which in Marra et al. (2016a) was not highlighted. However, scanty sedimentary deposits occur at these elevations in this area, where the outcropping terrains are mostly represented by the Monti Sabatini volcanic succession. Notably, thin layers of calcareous lacustrine muds, ca. 50 m thick, crop out at 72 m a.s.l. in Castel di Guido, and are overlain by the pyroclastic-flow deposit of Tufo Giallo di Sacrofano (285 ± 2 ka, Karner et al., 2001b; Sottili et al., 2010), which forms most of the hilltops of the 71-77 m paleo-surface (Marra et al., 2018c). We interpret these sedimentary strata as the remnants of an alluvial coastal plain, mantled by a thin cover of pyroclastic deposits.

4.2.4 Paleo-surface 61-67 m a.s.l.

No evident paleo-surface is associated with this class of elevations in the sector south of the Tiber mouth, except that pertaining to small, isolated plateaux, like at the Colle Rotondo locality (CR, Figure 8). The Colle Rotondo site is located on the flat surface of an E-W elongated hill, culminating 63.5 m a.s.l., bordered by the steep flanks of two convergent streams, 2.5 km east of the present coast, and 7.5 km north of Anzio (Figure 3). This is part of a series of hilltops ranging 61-67 m a.s.l., aligned along a narrow stripe of land defining a coastal terrace between Ardea and Anzio (pink triangles in Figure 3). This terrace is shifted inland, significantly, within the Ardea basin, paralleling the behavior of the inner edge of the 51-57 m terrace, as well as that of the two lower terraces of 34-43 m, and 22-27 m (Figure 3). Notably, in the coastal sector overlooking the most elevated area of TML, corresponding to the

98-108 m paleo-surface, only plateau points define the 60-67 m terrace, while almost no evidence of the 51-57 m terrace occurs in the coastal reach north of the Ardea basin, consistent with erosion due to tectonic uplift of this sector. In contrast, a well-defined 60-67 m terrace occurs at the northwestern margin of the lower area represented in Figure 3, facing the terminal reach of the Tiber Valley.

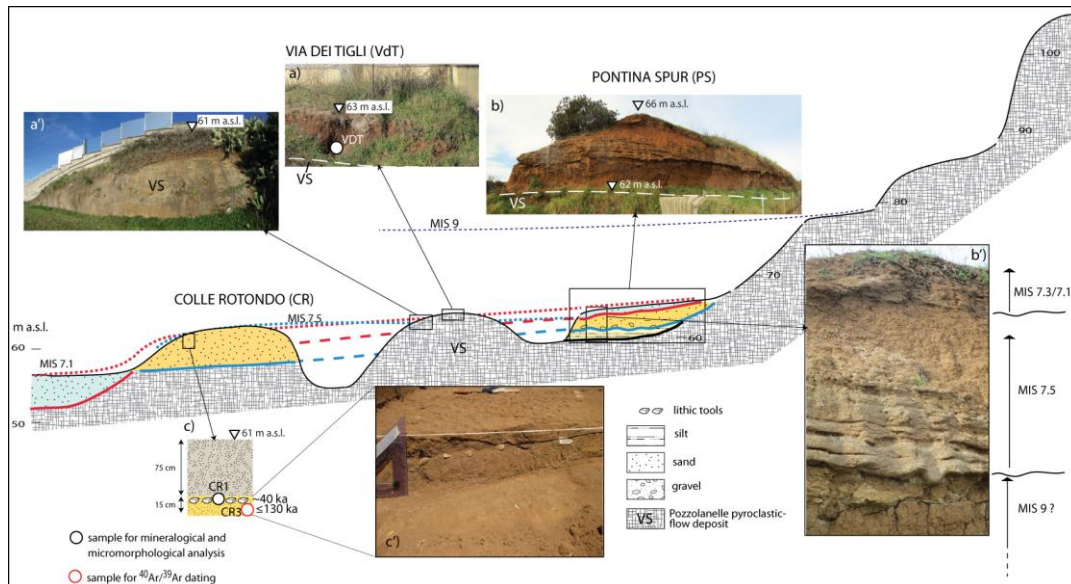


Figure 8 - Composite cross-section, constructed by projecting the Colle Rotondo (CR) site on an ideal profile passing by the Santa Procula (SP), Pontina Spur (PS), and Via dei Tigli (VdT) sites (see Figure 3 for location), aimed at showing the stratigraphic relationships between the sedimentary successions underlying the 60-67 m a.s.l. paleo-surface.

A pedogenized surface horizon consisting of brown sandy silt, heavily disturbed by ploughing, occurs in the upper 75 cm at CR (Figure 8c). It overlies a reddish-brown silty sand horizon, incorporating mm-sized Mn and/or Fe concretions (Figure 8c'). A large number of stone artifacts attributed to the Uluzzian culture (45-41 ka) was found within the upper portion of this sand layer, ranging in thickness from 6 to a maximum of 20 cm (Villa et al., 2018). One sand sample (CR1) collected within the archaeological layer was analyzed for micromorphology by Villa et al. (2016), while 39 sanidine crystals extracted from a sand sample (CR3) collected immediately below (see Figure 8c) have been dated as part of the present work.

A different geologic substrate characterizes the 60-67 m paleo-surface at two sites located in the northern portion of the Ardea Basin, Via dei Tigli (VdT) and Pontina Spur (PS) (Figure 3).

A ca. 80 cm thick, brown-reddish clayey paleosol overlies the PL at VdT (Figure 8a). Field surveys showed that the substrate of the 60-67 m paleo-surface in this area is represented by a pedogenized layer on top of the PL (e.g., Figure 8a'). One sample from this soil (VdT) has been analyzed for micromorphology.

A peculiar situation is observed at PS, where two fining-upwards successions overlie a third, faintly bedded fine sand deposit, which in turn overlies the PL (Figure 8b-b'). The two upper successions consist of a basal gravel layer, made up of reworked volcanic material with characteristic, large leucite crystals turned into analcime, suggesting provenance from the PL (Freda et al., 1997). The finer, upper part is also made up largely of volcanic sand. Both have evident fluvial origin. The lowest layer is a silty fine sand, of possible palustrine or alluvial origin. No sample was collected from this section, due to its very local significance, while a correlation with the other sections of the 60-67 m paleo-surface and a paleoenvironmental interpretation is provided in the cross-section of Figure 8.

The 60-67 m paleo-surface has a wide expression to the north of the Tiber (Figure 2).

However, no sedimentary succession is apparently associated with this paleo-surface, its geologic substrate consisting of different, older volcanic deposits, ranging 561-400 ka (e.g., Karner and Marra, 1998; Marra et al., 2016b), which form the hilltops in this area.

Consequently, the 60-67 paleo-surface in this area should be considered as a non-depositional terrace, possibly generated by uplift-induced erosional processes in the near-shore sector, similar to the higher level paleo-surface of 71-77 m in this sector.

4.2.5 Paleo-surface 51-57 m a.s.l.

This paleo-surface (red triangles in Figure 2 and 3) has a prominent expression in the Ponte Galeria area north of the Tiber mouth, where solid geochronologic constraints correlate it with MIS 7, as noted in Marra et al. (2016a). It is rather well preserved along the southeastern side of the Tiber Valley, south of the river mouth, and in the southernmost sector between Ardea and Anzio, while it disappears along the coastal reach facing the TML morpho-structural height (Figure 3). However, two fragments of coastal terrace are preserved immediately north of this sector, and one of these (Castel Romano -CSR) provides good exposure of the terrains underlying the paleo-surface. At CSR a large level area at elevations ranging 51-56 m a.s.l. is bordered to the west-northwest by a steep, 6 m high scarp (Figure 9a), separating it from the other wide level area of Podere Carafa, ranging 71-79 m a.s.l. (see Figure 3).

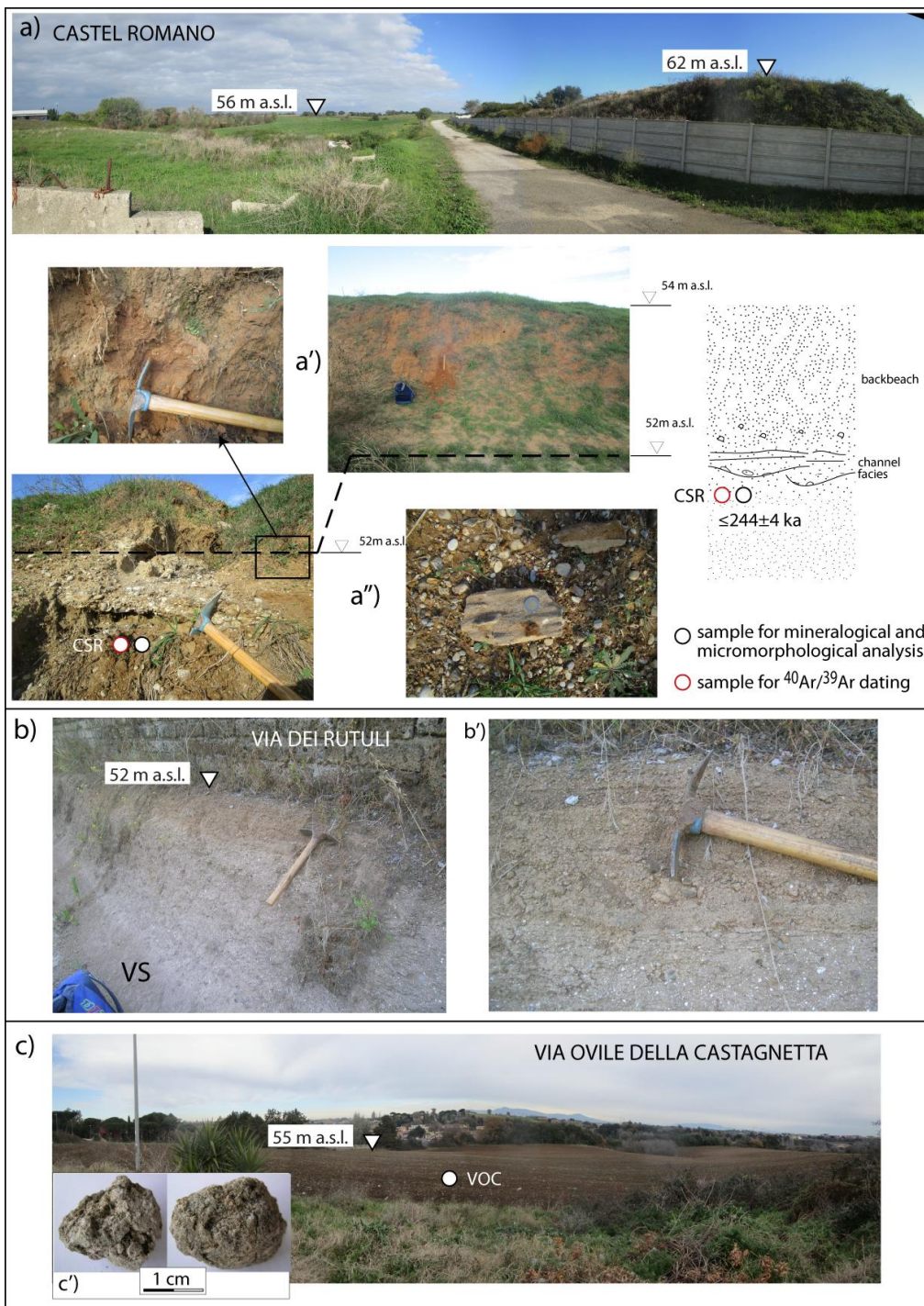


Figure 9 - Photographs and stratigraphic schemes showing the 51-57m a.s.l. paleo-surface and the sections from which samples analyzed in the present study were collected. See text for comments.

The 60-67 m terrace is not preserved between the two paleo-surfaces in this area, which are connected by a gentle incline degrading from ca. 70 m to 62 m a.s.l., behind the sub-vertical scarp. The 51-56 m paleo-surface at CSR is dissected by a gully exposing on its banks a reddened, massive sand deposit, 2 m thick (Figure 9a'), overlying a ca. 50 cm thick layer with gravel lenses and sandstone horizons with ripple marks (Figure 9a"). This braided channel facies overlies a massive sand deposit in which sample CSR for mineralogical analysis and $^{40}\text{Ar}/^{39}\text{Ar}$ dating was collected.

A different geologic substrate represented by the PL characterizes the 51-57 m paleo-surface within the Ardea Basin. However, exposure at Via dei Rutuli (VR, see Figure 3) provides evidence of a conglomeratic layer above the PL at 52 m a.s.l. (Figure 9b), which testifies the occurrence of a transgressive deposit that should be considered the coastal deposit associated with the 51-57 terrace in this area. It is a bedded, fining upward, 50 cm thick sand and gravel layer, containing well-rounded scoria clasts from the underlying pyroclastic deposit, which is erosionally truncated at the top (Figure 9b'). Evidence from another site within the Ardea basin (Via Oville della Castagnetta -VOC, Figure 3) suggests that a fine-grained, lagoon deposit forms the upper portion of the 51-57 terrace in this area. Here, a wide paleo-surface around 55 m a.s.l. (Figure 9c) consists of a brown, mature paleosol in which one sample (VOC) was collected and analyzed for micromorphology. The occurrence of abundant, rounded calcareous concretions (Figure 9c'), which are uncommon in shallow soils developed directly upon the siliceous volcanic deposits, suggests the presence of a horizon of calcareous mud, as typically observed in the lagoon deposits of the MIS 7 Vitinia Formation (Karner and Marra, 1998) associated with the 51-57 paleo-surface in the northern coastal sector.

4.3 Micromorphological analyses

Results of thin section observations are summarized in Table 1.

TS ¹	Microstructure	Lithology	Groundmass ²	c/f ratio	Rel Dist ³	Pedofeatures
TML-CC	-	Matrix: 15 -20% fine sands (quartz; rare feldspar; chert; metamorphic rock fragments) Inside nodules: well sorted fine sands ($\pm 45\%$) (quartz; feldspar;	Orange (PPL) clay with SS and GS bfabric	20/80 (matrix) 50/50 (nodules)	OP (matr.) SSP (nod.)	Matrix: layered clay coatings and infillings, limp and

		chert; metamorphic rock fragments; pyroxene)				silty clay, broad extinction lines, frequent.
CR1	Basic MS type: close porphyric	Fine sand (5%); Medium sand (60-65%) Lithology: quartz; feldspar; chert; pyroxene; metamorphic rock fragments; epidote. Sub-rounded and sub-angular grains.	Reddish (PPL) clays with SS and GS b-fabric	70/30	CP	Limpid clay coatings and infillings, 1st order yellow interference colors; broad extinction lines, occasional superimposed Fe coatings.
VDT	Subangular blocky, moderate	Very fine sand (5-10%); Fine sand (5%); Medium sand (5-10%) Lithology: quartz; chert; pyroxene (rare); Sub-rounded and sub-angular grains.	Orange (PPL) clay with CS and GS b-fabric	20/80	OP	Limpid clay coatings, strongly deformed, frequent. Disorthisc Fe/Mn nodules, typic and concentric, frequent, rounded.
VOC	Basic MS type: single-spaced porphyric	Very fine sand ($\pm 5\%$); Fine sand (15-20%); Medium sand (25-30%) Lithology: quartz; feldspar; chert; pyroxene; amphibole; volcanic scoria (rare); metamorphic rock fragments. Sub-rounded and sub-angular grains.	Yellowish (PPL) clays with GS b-fabric	60/40	SSP	Limpid clay coatings, strongly deformed, frequent. Disorthisc Fe/Mn nodules, typic and concentric, frequent, rounded.

Table 1 – Description of thin sections

¹ TS = Thin Section

² B-fabric: SS = Stipple speckled; PS = porostriated; GS = granostriated; CS = cross striated

³ Rel Dist = Related distribution pattern: CP = close porphyric; SSP = single-spaced porphyric; OP = open porphyric

4.3.1 Concretionary layer from Tenuta Monte di Leva: sample TML-CC

Micromorphological analysis of this sample collected from the TML concretionary layer shows that the nodules are iron and manganese concretions that entrap sediments differing from those in the surrounding groundmass. The main differences between the sediments within the nodules and those in the matrix around them are as follows:

- (a) The degree of sorting, which inside the nodules is good, with grains in the fine sand class, indicating that the nodules formed in aeolian or alluvial sands (e.g., channel facies).
- (b) The lithology: the matrix consists only of weathering resistant species, whereas in the nodules some volcanic minerals (pyroxenes – Fig. S1) are preserved, and feldspar (e.g., microcline) is more abundant than in the surrounding matrix.

The matrix around the nodules shows the effects of marked pedogenesis. It is in fact very clay-rich and in the coarse fraction only weathering resistant material is preserved (quartz, chert,

metamorphic rock fragments – predominantly quartzite). Clay coatings, pertaining to several superimposed episodes of clay illuviation, are very strongly developed (Fig. S2). They occur as superimposed limpid and silty clay coatings or as coatings deformed due to shrink-swell phenomena.

Albeit that the nodules may be allochthonous (i.e., formed elsewhere and then transported and re-deposited after being eroded), observations attest that they contain remains of the former parent material on which pedogenesis has taken place, “preserving” it from successive weathering. Weathering and pedogenesis subsequently affected the groundmass but were impeded within the nodules.

4.3.2 Sand deposit from Colle Rotondo: sample CR-1

The sand fraction is composed of a mixture of siliciclastic and volcanoclastic (i.e. pyroxenes – augite) mineral species. The moderate sorting, the grain size centered on the medium sand granulometric class, and the slight rounding of the grains are compatible with an aeolian (backbeach) sediment. There are no traces of reworking due to surface runoff or similar water and gravity-triggered slope processes. Pedogenesis is at an initial stage, especially compared to other samples from this study. Incipient reorganization of the groundmass, giving rise to a stipple-speckled b-fabric, is observed. Weak traces of incipient clay illuviation, such as thin clay coatings around skeletal grains, also point to an initial/moderate level of pedogenesis (Fig. S3). The weatherable minerals in the coarse fraction – especially pyroxenes – are abundant and do not show traces of weathering.

4.3.3 Paleosol from Via dei Tigli: sample VDT

This sample shows the highest degree of pedogenic weathering amongst the analyzed samples. The abundant clay in the groundmass shows orange-red colors resulting from the strong oxidation, and the clay are the outcome of repeated cycles of clay illuviation. Strong vertic processes (i.e.: internal turnover of soil material) led to the digestion of the illuvial clays in the fine mass and to the formation of strongly developed cross-striated and grano-striated b-fabric types (Fig. S4, S5). Also the nodules of iron and manganese owe their morphology to the strong shrink-swell phenomena in the sample (which led to the formation of concentric nodules with strong rounding). The coarse fraction is predominantly composed of weathering-resistant species (quartz and chert), albeit minor amounts of pyroxenes and unaltered volcanic glass are still present. The latter might derive from a ‘fresher’ or more recent input of volcanoclastic material into the soil during its formation. The poor sorting, sub-

angular morphology and medium-fine sand grain size of the siliciclastic fraction do not match the expected characteristics of an aeolian input, strongly suggesting an alluvial/colluvial origin.

4.3.4 Paleosol from Via Oville della Castagnetta: sample VOC

The sorting of the coarse fraction is low. The sample has the highest percentage of volcanic mineral grains (pyroxenes and amphiboles – see Fig. S6) in the studied set, included the loose sand samples. The fine fraction derives from clay illuviation, which ultimately triggered vertic processes and the digestion of clay coatings within the groundmass, the development of a grano-striated b-fabric, and the formation of concentric iron and manganese nodules. Grains are predominantly in the fine and medium sand fraction, and show subrounded and rounded morphologies. The low sorting and the rounding of iron and manganese nodules indicate reworking and redeposition of the material. The presence of rare calcite infillings indicates re-carbonation of the profile due to the effect of a dissolved carbonate-rich groundwater table (Fig. S6). Abundant, large (1-2 cm) carbonatic nodules also occur in the deposit.

4.4 Mineralogical analyses in thin section

4.4.1 sample TML-SA

Due to the granulometric bias introduced by sieving, it is not possible to ascertain the sedimentary environment in which the deposit formed through thin section observation. Nevertheless, it can be said that TML-SA is characterized by scanty medium and coarse sand fraction, and by fine material possibly indicating pedogenesis. Indeed, the fine material was observed before the sieving and also after it, especially in the form of “pseudosands” which survived the sieving procedure. The nature of the sand grains is essentially siliciclastic (Table 2), with a very minor volcanoclastic fraction and lack of volcanic scoriae. Grains have a subangular morphology.

Minerals	TML - SA	PC-SA	CSRM-SA
	%	%	%
Quartz	64	66	35
Metamorphic rock fragments	20	19	35
Chert	12	10	16
Feldspar	3	2	5
Pyroxene	1	3	8
Amphibole	1	0	0
Volcanic scoria	0	0	1

Total siliciclastic %	98	97	91
Total volcaniclastic %	2	3	9
<i>Counted grains (n)</i>	152	156	154

Table 2: results of petrographic determination of sands

Quartz, chert, metamorphic rock fragments (mainly quartzite with minor amounts of schist) and feldspar have been grouped under the “siliciclastic” category. Pyroxene (mostly augite and monocline pyroxene, diallagio), amphiboles (green and brown hornblende) and volcanic scoria belong to the “volcaniclastic” category.

4.4.2 Sand deposit at Podere Carafa: sample PC-SA

The sand displays strikingly similar grain composition (Table 1) and morphology as that of sample TML-SA.

4.4.3 Sand deposit at Castel Romano: sample CSR-SA

This sand sample is characterized by medium grain size with a subrounded morphology and no fine matrix. Mineralogical composition displays a higher percentage of volcanic species in comparison with the other sand samples (Table 1).

4.5 X-ray and SEM analysis

Results of diffractometric analyses are summarized in the diagrams of Figure 10.

Calcic clinopyroxene is ubiquitous in the pyroclastic rocks of the Colli Albani volcanic district. In addition, amorphous material derived from the weathering of volcanic glasses is typical of soils developed on pyroclastic rocks (generally, this soil component is identified in the RDX by the increase of counts in the region at lower 2Θ). Consequently, the height of clinopyroxene peak at $2\Theta=29.85^\circ$, as well as that of amorphous material at $2\Theta=4^\circ$, with respect to quartz peak at $2\Theta=26.65^\circ$ in the RDX can be assumed as an indicator of the abundance of volcanic components forming the soil. This provides an index (i.e. $Qtz/(AM+Cpx)$ in Table 3) to distinguish the soils developed above a primary volcanic substrate (Index <6) from those overlying sedimentary deposits (Index >6).

Notably, quartz is present in all the soils developed above volcanic deposit and its abundance generally increases with decreasing depth as evidenced by magnitude of the peak at $2\Theta=26.65^\circ$ (Q1 Figure 10a). Quartz is practically absent closer to the base of the soil in VTB-1, and is scarce in the middle of the soil in VTB-2 and in Monte Migliore (MM). However, it is also abundant in the middle of VVL and VL, where the Q1 peak is comparable with that of all the surface samples. A marked quartz peak is present in sample VdT-2, from the soil developed

above the Villa Senni deposit on the 61-67 terrace, for which the siliciclastic fraction has been investigated in thin section for micromorphology on sample VdT-1. However, excluding the sample VCR-1, notably the closest one to the inferred sedimentary/volcanic transition in Figure 11, all the soils developed above volcanic deposit show higher amount of AM+Cpx (>12) in comparison with the others soils analyzed in this study (Table 3).

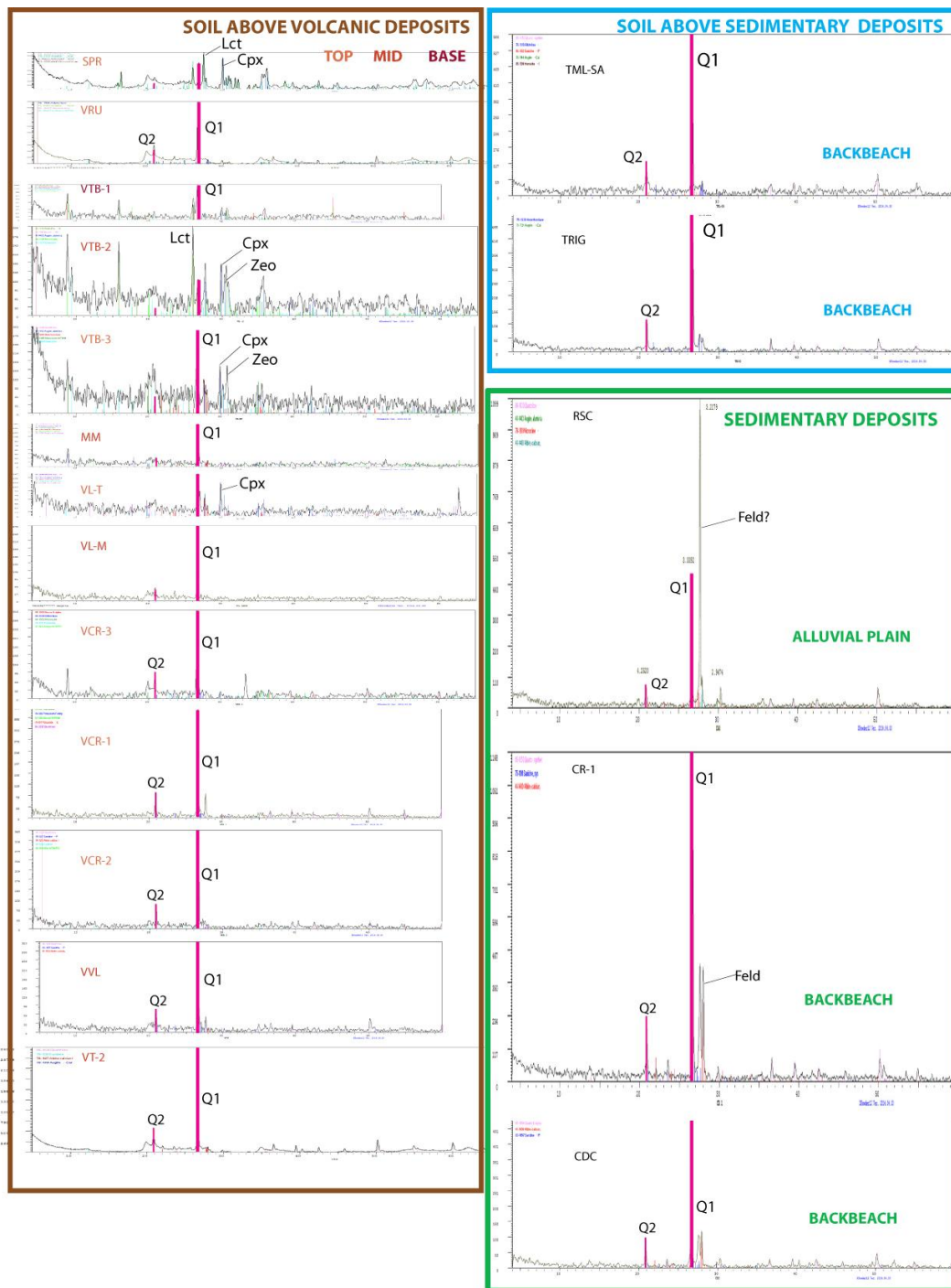


Figure 10 - Diffractograms of the soil and sediment samples. In inset a' diffractograms are... Vertical axes are normalized to the same scale; full-resolution original diagrams are provided in Suppl. Mat. #1B. See text for comments.

Moreover, quartz abundance decreases with the distance from the inferred paleo-shoreline in soils developed above the volcanic substrate. In order to verify this observation, we have collected two samples in the inland sector at the foot of the Colli Albani peri-caldera ring (SPR and RUT, Figure 11) and we have normalized results of diffractometric analyses performed with a different equipment (see Methods in Supplementary Material #2) by re-analyzing samples VTB-1 and VTB-3 with them (Table 3). As shown in Figure 10 and Table 3, Q1 peaks and AM+Cpx/Qz are the highest one for these samples.

Apart for the discriminating AM+Cpx/Qz ratio, diffractograms of soils above sedimentary deposits differ from those above volcanic deposits only for the slightly larger magnitude of the main quartz peak Q1, and for the presence of a second quartz peak close to 10 (Q2). These peaks are much higher in the sediment samples which also display a remarkable peak corresponding to the pyroxene. Finally, the smaller magnitude of the quartz and pyroxene peaks in the fine sediment sample CDC suggests that magnitudes are also proportional to grain size of the siliciclastic component.

Abundance, dimension and morphology of the Quartz and K-feldspar grains occurring in selected samples (VTB-1, TML-SA, VCR-1, CR1) have been analyzed at the SEM and discussed in section 5.1. Microphotographs are provided in Supplementary Material #2.

	SOILS ABOVE VOLCANIC DEPOSITS															SOILS ABOVE SEDIMENTARY DEPOSITS				
	VTB-1	VTB-2	VTB-1	VV	VL-M	VL-T	MM	VTB-1*	VTB-3*	VRU*	SPR*	VdT-2*	VCR-3	VCR-2	VCR-1	TRIG	TML-SA	RSC	CDC	CR-1
Amorphous	305	240	8000	58	54	121	45	68	9900	6100	8500	4750	80	70	30	52	59	55	45	110
Qtz	290	122	8000	320	270	147	150	0	20700	15977	6650	26343	316	349	394	520	586	1099	501	1168
Cpx	165	165	11500	0	10	118	15	40	9300	750	8000	550	25	0	10	20	20	40	20	0
TOT	760	527	27500	378	334	386	210	108	39900	22827	23150	31643	421	419	434	592	665	1194	566	1278
Amorphous	40	46	29	15	16	31	21	63	25	27	37	15	19	17	7	9	9	5	8	9
Qtz	38	23	29	85	81	38	71	0	52	70	29	83	75	83	91	88	88	92	89	91
Cpx	22	31	42	0	3	31	7	37	23	3	35	2	6	0	2	3	3	3	4	0
TOT	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Qtz/Cpx+AM	0,6	0,3	0,4	5,5	4,2	0,6	2,5	0,0	1,1	2,3	0,4	5,0	3,0	5,0	9,9	7,2	7,4	11,6	7,7	10,6
Cpx+AM	62	77	71	15	19	62	29	100	48	30	71	17	25	17	9	12	12	8	11	9

Table 3 - X-ray powder diffraction (XRPD) data. Summary of absolute abundances of mineral phases in the analyzed samples (*samples analyzed with a different equipment, see Methods in Supplementary Material #2).

4.6 $^{40}\text{Ar}/^{39}\text{Ar}$ data

Single crystal age data for the three analyzed samples are reported in Table 4. Full analytical data are provided in Supplementary Material #3.

4.6.1 Sample CR3

Thirty-nine sanidine crystals extracted from the sand sample collected ca. 90 cm below the ground surface in Colle Rotondo provided a wide age spectrum, ranging 1.31 through 0.13 Ma. A youngest population of eight crystals yielded a weighted mean age of 134 ± 3.5 ka.

4.6.2 Sample TML-SA

Forty-one sanidine crystals extracted from the sand sample collected ca. 60 cm below the ground surface in Tenuta Monte di Leva provided ages ranging 1.34 through 0.15 Ma. A youngest population of six crystals yielded a weighted mean age of 169 ± 11 ka.

4.6.3 Sample CSR-SA

Twenty sanidine crystals extracted from the sample collected in the fluvial sand cropping out in Castel Romano provided ages ranging 0.80 through 0.23 Ma. A youngest population of four crystals yielded a weighted mean age of 244 ± 4 ka.

4.6.4 Sample RSC-SA

Twenty sanidine crystals extracted from the sample collected in the fluvial sand cropping out in Riserva Carpineto provided one isolated, youngest crystal of 298 ± 3.5 ka. The majority of the crystal ages are spread in the interval 398-468 ka, with three oldest crystals ranging 523 - 581 ka.

5. Discussion

5.1 Soils and paleo-surfaces

Analysis of soil samples for the present study has been conducted aimed at identifying their sedimentologic and petrographic features, in order to understand their origin and the paleogeographic conditions in which they formed. Pedologic considerations and a complete study of the processes involved the formation of these soils, as well as laboratory granulometric analyses are beyond the scope of the present work. Our main scope is to verify to what extent the present ground surfaces characterized by the same elevations range represented in Figure 2 and 3 can be considered indicative of the original paleo-surfaces representing the ancient coastal settings. In particular, we want to quantify the possible amount of later deposition, or erosion, which may have increased or decreased, respectively, the average elevation of these paleo-surfaces, therefore affecting our estimation of the sea-level related with the corresponding coastal terrace.

When studying the composition of the soils developed above the reconstructed paleo-surfaces, some preliminary considerations are necessary. In particular, when the paleo-surfaces of highest order are considered (i.e. those ranging 98-108, 80-89, and 71-79 m a.s.l., Figure 3), we must realize that the sub-horizontal attitude of these isolated, plateau-like sectors precludes alluvial sedimentation, almost completely. Furthermore, the whole catchment area drained by these paleo-surfaces is developed above volcanic deposits. Therefore, the siliciclastic component of the soils above the paleo-surfaces of this sector, which in the X-ray diagrams is sometimes predominant, can only have the following two origins:

- i. it can be a back-beach to coastal plain sediment originally deposited above the volcanic substrate when the paleogeographic conditions allowed (i.e.: before the regional uplift, when the paleo-surface represented a coastal environmental setting) (BB and AL in Figure 11a);
- ii. it can be an aeolian sediment (i.e., loess-like) accumulated above the volcanic deposits through air-fall emplacement and successively diffused within the soil by vertic processes (i.e.: internal turnover of soil material originated by pedogenetic processes).

Recognizing the origin of this siliciclastic sediment is therefore fundamental in order to reconstruct the paleogeographic setting of these paleo-surfaces, correctly, as shown in Figure 11, in which the paleogeographic scenario is illustrated. The dashed green line in Figure 11 separates the sampling sites where field observation have shown that the present soil overlies sedimentary sand deposits (to the southwest), from those where the soil is developed above the volcanic deposit of Pozzolanelle (to the northeast), as reported also in the cross-section of Figure 12. The oblique green lines indicate the area where the siliciclastic fraction in the analyzed soils is predominant.

Composition of the analyzed soils overlying the volcanic deposit of Pozzolanelle, with abundant quartz and feldspar, combined with micromorphological and SEM analyses which confirm the sedimentary origin of the quartz grains but rule out an aeolian (loess-like) origin, at least for the larger fraction ($>200\ \mu\text{m}$; Figure S7), demonstrate that these soils affect thin ($\leq 1\ \text{m}$) layers of alluvial and backbeach, predominantly siliciclastic deposits. In keeping with this interpretation, quartz abundance strongly decreases in soil samples collected in more inland locations (SPR, RUT), far from the inferred paleo-coastline (Figure 10).

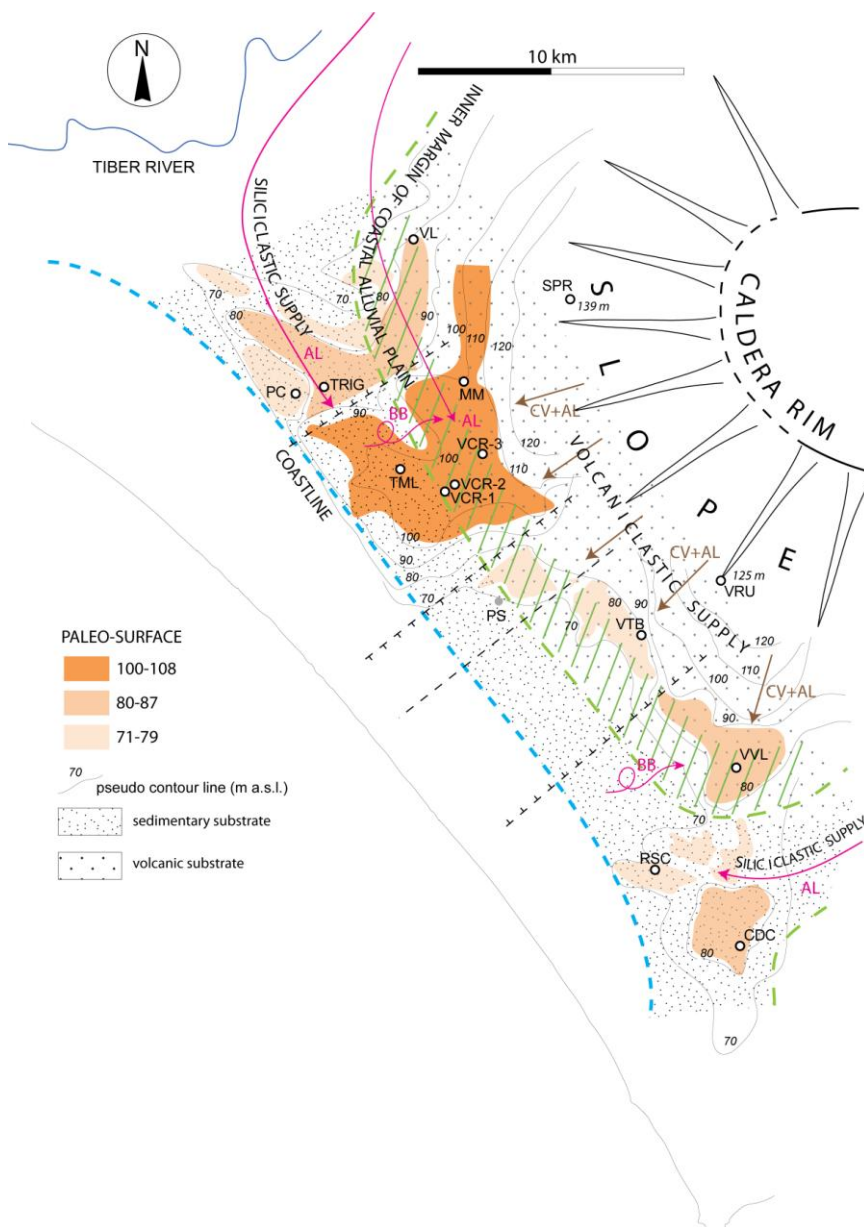


Figure 11- Paleogeographic reconstruction of the MIS 9 coastal setting. Stratigraphic investigations and sedimentologic, micromorphologic, mineralogic and petrographic analyses on sediment and soil samples have allowed to detect a transitional zone (oblique green dashes) corresponding with the inner margin of the coastal plain, where a thin horizon of backbeach to alluvial deposits overlaps the volcanic substrate. (see also cross-section in Figure 12a). This reconstruction evidences the occurrence of an original, homogeneous paleo-surface, subsequently disrupted and dislocated by tectonic movements, which gave rise to three main flat sectors at elevations ranging 100-108, 80-87, and 71-79 m a.s.l. (see text for comments).

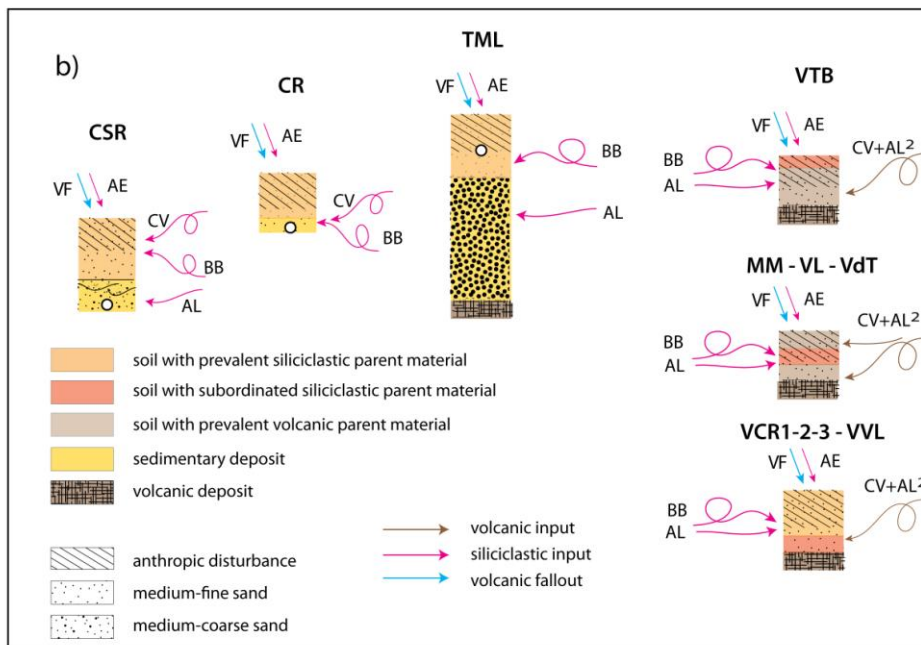
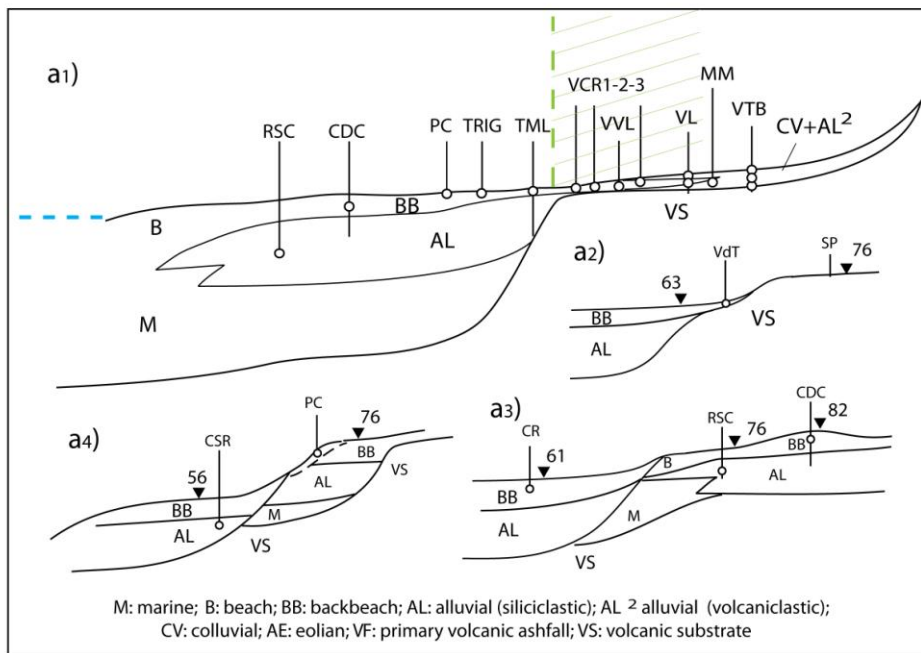


Figure 12 - a1-4) Cross-sections restored from tectonic dislocation showing the original paleogeographic and sedimentary settings reconstructed in the area where the soil and sediment samples were collected. b) Origin of the different sedimentary inputs contributing to the formation of the deposits and the related soils at the top of the paleo-surfaces reconstructed in the present study. See text for comments.

Alluvial/colluvial volcanic material (CV+AL in Figure 11b and 12), derived from the rocks cropping out at the inner margin of the coastal alluvial plain (green dashed area in Figure 11), were also continuously mixing with the alluvial and backbeach, predominantly siliciclastic deposits transported by the Tiber River and deposited in the coastal plain. Moreover, air-fall material including either loess-like sediment (AE in Figure 12b), or as primary air-fall volcanic ash (VF in Figure 12b), also progressively accumulated above this soils and was diffused by vertic processes into the sub-surface horizon. To this aeolian fraction must be ascribed part of the K-feldspar observed in this section and evidenced in the diffractograms, as well as part of the finest siliciclastic component.

Such an air-fall contribution must be extended to the soils developed above the sedimentary deposits, in which the volcanic component is also represented by re-deposited mineral species of the underlying sedimentary substrate, incorporated in the soil through colluviation, surface water and wind transport (CV in Figure 12b).

These mechanisms are envisaged in Figure 12, showing the different paleogeographic and sedimentary settings reconstructed in the area where the soil and sediment samples were collected. The age spectra provided by sanidine crystals extracted from the lowest portion (unaffected by agricultural disturbance) of the backbeach deposits above which the soils of the 98-108 and of the 61-67 paleo-surfaces have developed (TML-SA, CR3; Figure 13), compared to that of the "sealed" sedimentary deposit of the fluvial facies (RSC-SA, CSR-SA), provide further insights to the processes described above.

5.2 Age of the paleo-surfaces

Youngest crystal ages of 232 ± 20 and 298 ± 4 ka yielded by sedimentary samples collected in the alluvial facies (coastal plain) of the 51-57 m and of 71-79 m paleo-surfaces (CSR-SA and RSC-SA) support correlation with MIS 7 and MIS 9 for the corresponding coastal terraces, as discussed in the following sections.

Similarly, crystal ages of the samples collected from the backbeach facies at the top of the 98-108 m and 61-67 m paleo-surfaces provide time constraints on the sedimentary processes that acted in the time span following retreat of the coastline leading to progressive impoverishment of sediment supply.

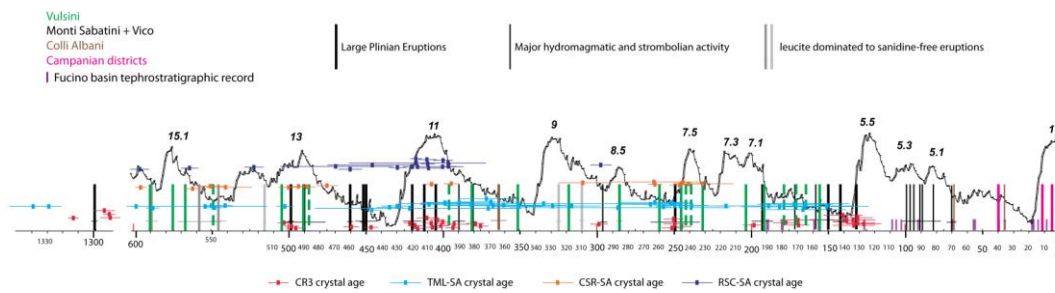


Figure 13 - Crystal age spectra for the four sedimentary samples dated in the present study. Each cross represents the age of one dated sanidine crystal with the associated analytical error at 2σ . Comparison with the major eruptions occurred at the districts of the Roman Comagmatic province is provided. Each bar represents one eruption age (see Suppl. Mat. for details and references). Comparison with the oxygen isotope curve (Lisiecki and Raymo, 2005) is also shown. See text for comments.

These age constraints are obtained by comparing the sample crystal ages with the eruptive histories of the volcanoes of the Latium Region, as provided in Figure 13. In considering the eruptive histories of the volcanic districts of Central Italy to compare age spectra yielded by the analyzed sedimentary samples reported in Figure 13, some preliminary considerations should be made.

- i- These volcanoes are part of the "Roman Magmatic Province" (Conticelli and Peccerillo, 1992), characterized by a K-rich geochemistry which accounts for the diffuse presence of sanidine ($KAlSi_3O_8$) and leucite ($K[AlSi_2O_6]$) crystals, which also constitute the means of $^{40}Ar/^{39}Ar$ dating. However, while sanidine is a very resistant mineral species, leucite is highly sensible to weathering and easily alters to analcime ($NaAlSi_2O$): a process implying loose of K and compromising $^{40}Ar/^{39}Ar$ dating. Indeed, fluviially transported and beach deposits of several hundred kyr lack pristine leucite crystals. Therefore, in Figure 13 we have not reported all the sanidine-free eruption units (i.e., most of those of the Colli Albani volcanic district, see Gaeta et al., 2016 and references therein), while we have indicated those dominated by leucite (for which a lesser statistical occurrence is expected).
- ii- When incorporation of crystals derived from primary fallout deposits is considered, the overall eastward regional winds and a consequent dispersal axis should be considered, along with the distance from the source area. Therefore, the major source of fallout deposits are the MSVD and Vico, while deposits from the Colli Albani and the Campanian districts have a low probability of representation in the stratigraphic record. One exception is represented by the sanidine-bearing activity of the Albano Center spanning 70 through 36 ka (Giaccio et al., 2009, and ref.), for which the small vent distance should have led to a well-represented crystal population, as also evidenced by outcrops in the southeastern area of the CAVD (e.g., Cisterna

di Latina, Latina Plain; Gatta et al., 2018, Sevink et al., 2018). Moreover, huge explosive eruptions like the Campanian Ignimbrite (39 ka), Neapolitan Yellow Tuff (12 ka) and Avellino pumice (4 ka) have provided widespread tephrostratigraphic markers in Latium (e.g., Giaccio et al., 2017).

iii- The youngest eruptions should be better represented given the larger outcrop areas of the products in comparison with the older ones, which are buried under more recent cover. This reinforces the principle that a lack of crystals younger than the youngest population is evidence of deposition prior to the immediately following eruption.

Consistent with the considerations above, Figure 13 shows that the age spectra of sanidine crystals extracted from the four sand samples record a long eruptive history, ranging 0.60 - 0.13 Ma, plus one isolated cluster around 1.3 M. All crystal ages ≤ 0.6 Ma match known eruptions of the Monti Sabatini, Vico and Vulsini volcanoes (Palladino et al., 2010; Sottili et al., 2010; Marra et al., 2014, and ref. therein), while the oldest age matches that of early activity of the Cimini volcanic complex (Everdin and Curtis, 1965, Nicoletti, 1969), located in the upper Tiber Valley east of Vico. In contrast, all the eruption ages known from the literature that are missing in the dated crystal populations, besides the sanidine-free Colli Albani products, also correspond to sanidine-free or leucite-dominated products from Vico and Monti Sabatini volcanic districts (Cioni et al., 1987; Sottili et al., 2004; Perini et al., 2004; Masotta et al., 2010; Marra et al., 2014).

Based on these premises, in the following we discuss sample age implications on assessing the age of the related paleo-surfaces.

5.2.1 CSR-SA - 51-57 m paleo-surface

Based on the sedimentary features of the underlying deposits and the top elevation ranging 51-57 m a.s.l. (Figure 9a-a"), the Castel Romano paleo-surface is interpreted as a backbeach context, including the dune system superimposing the delta plain, developed during highstand of MIS 7.3/7.1. Loose sanidine crystals occurring in the sand deposit of the braided fluvial channel facies (Figure 9a'-a") yielded a youngest age of 232.3 ± 19.8 ka, part of a statistically significant youngest population of 244.0 ± 3.8 ka (Table 4). Such datum has to be considered a terminus post-quem which implies an age \leq MIS 7.5 (Figure 13), excluding and age within MIS 9 and supporting correlation with highstand of the MIS 7.3/7.1.

5.2.2 RSC-SA - 71-79 m paleo-surface

The age spectrum of sample RSC-SA, collected within the alluvial plain deposit underlying the 71-79 m paleo-surface at Riserva Carpineto, spans 581 - 398 ka, with a youngest crystal of 298 ± 3.5 ka (Table 4). Most crystal ages are clustered between 460 and 390 ka, coincident with the large explosive phases emplacing sanidine-bearing products at Vico and Sabatini in this time span (Figure 13). In contrast, no crystal deriving from the Villa Senni eruption unit occurs in the dated sample, despite the sampled deposit overlies the Pozzolanelle eruption unit of 365 ± 4 ka, consistent with the lack of sanidine phenocrystals in the Colli Albani products. The age of one single crystal yielding 298 ± 3.5 ka has a poor statistical weight, and should be regarded as broadly indicative of the lack of crystals younger than 300 ka. However, it supports correlation with MIS 9 for the 71-79 m paleo-surface of Riserva Carpineto, suggesting that sedimentation in the alluvial plain was sealed in the late stages of the MIS 9 highstand, excluding an age within MIS 7, while an age within MIS 11 is also excluded by the fact that the sand deposit of Riserva Carpineto overlies the 365 ± 5 ka Pozzolanelle pyroclastic-flow deposit.

5.2.3 CR3 - 61-67 m paleo-surface

Based on its sedimentologic features and the elevation ranging 61-67 m a.s.l., the Colle Rotondo paleo-surface is interpreted as a backbeach context, either part of a dune system or of a coastal alluvial plain, developed during highstand of MIS 7.5 (Figure 14a).

When the crystal ages from CR3 (red crosses in Figure 13) are compared to the eruptive histories of the volcanoes of the Latium Region, it is apparent that no eruption younger than 134 ± 3.5 ka is recorded by the Colle Rotondo sand deposit. Indeed, given the large number of dated crystals (39) and the wide age spectrum observed, the lack of any crystal from the eruptive activity since 99 ka (see Figure 13) strongly suggests that the sample age should be constrained between 132 and 99 ka. In particular, a large hydromagmatic phase occurred in several volcanic centers of the MSVD, including Baccano, Stracciapappe, Le Cese, Acquarello, Piana dei Falliti and Martignano, 132 ± 2 through 70 ± 3 ka (Sottili et al., 2010; Marra et al., 2019b). While the earliest eruption that occurred at Baccano at 132 ± 2 ka is evidently recorded by sample CR3, the lack of crystals from any later eruption strongly suggests a terminus ante-quem of ca. 99 ± 3 ka (age of the products of the 2nd Baccano unit, erupted at the beginning of the multi-vented hydromagmatic activity that continued until 70 ± 3 ka). Although this age boundary to the deposit is in conflict with the attribution to the Uluzzian for the lithic industry recovered at Colle Rotondo (Villa et al., 2018), we note that sample CR3 was not collected in the stratum in conjunction with the artifacts, but in a side excavation.

Therefore, its correspondence with the archaeological layer is not safely established and provenance may be from the immediately underlying older substrate. In this latter case, the occurrence of the Uluzzian lithic assemblage at ca. 80 cm depth suggests that the overlying package of sediment accumulated during the last 40 ky. Such an accelerated accumulation may be linked with recent anthropic activity (e.g., agriculture), triggering soil mobilization. In contrast, the apparent age of ~134 ka for the sand layer at 80 cm depth does not conflict with an inferred age of 250-200 ka within MIS 7 for the Colle Rotondo paleo-surface, as discussed hereby based on a detailed analysis of the $^{40}\text{Ar}/^{39}\text{Ar}$ dating results.

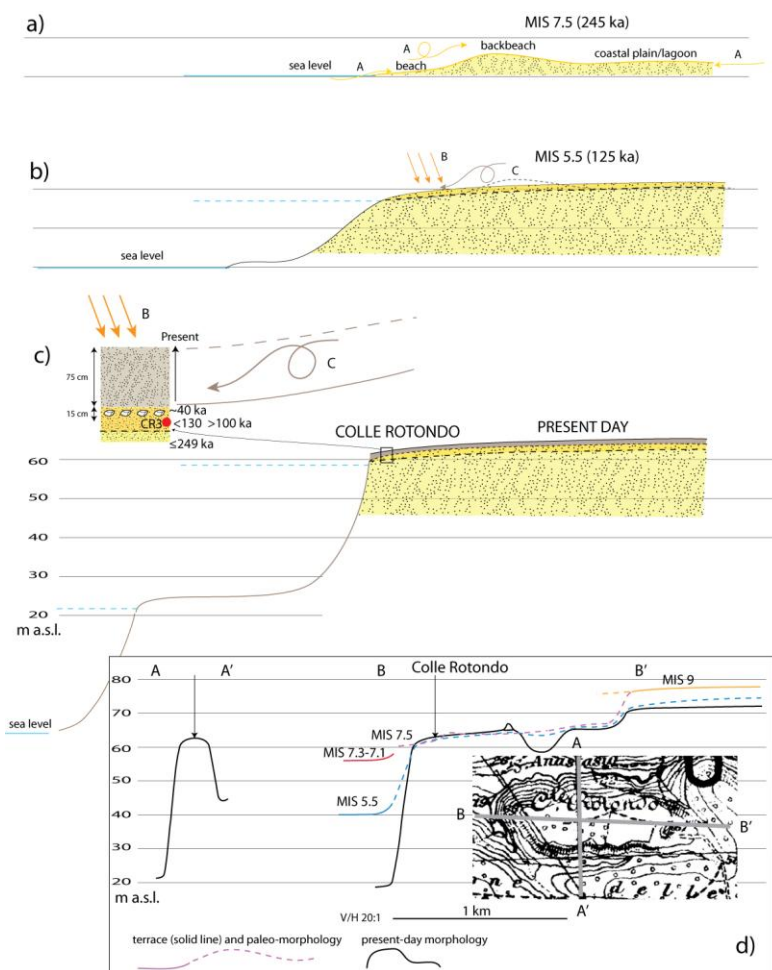


Figure 14 - Geomorphological and paleogeographic evolution of the Colle Rotondo plateau (see text for step by step comment and explanation).

Like in the case of the sedimentary deposit sampled at Castel Romano which yielded a youngest crystal age of 232 ± 20 ka, consistent with a deposition age corresponding to the highstand of MIS 7.3-7.1 (i.e. 220-200 ka), an age ≥ 245 ka is expected for the fluvial/beach

sedimentary deposit at Colle Rotondo (supply A in Figure 14a) incorporating crystals derived from erosion and re-deposition of the volcanic rocks erupted before that time, corresponding to highstand of MIS 7.5 (i.e., 245 ka, see Figure 13). However, a progressively younger age is expected for the backbeach deposit deriving from mixing of wind-blown sediment previously deposited (supply C in Figure 14b) with crystals deriving from primary eruptions occurring in the following time span (supply B in Figure 14b). Sample CR3 from Colle Rotondo yielded a statistically significant (8 crystals) youngest crystal population of 134.2 ± 3.5 ka which is characterized by significantly larger associated errors in comparison with the older populations (see Table 5). In particular, these crystals yielded an average associated error of ± 11 ka (corresponding to 8.2% when an age of 134 ka is considered) in comparison with an average associated error of ± 5.4 ka for the 23 crystals yielding ages spanning 249.9 - 503.2 ka (corresponding to 2.2% - 1.1%). These larger errors are due to the systematically smaller dimensions of these crystals, evidencing their different means of transport in comparison with that affecting the oldest ones, i.e.: wind vs. water. When this distinction is taken into account, we find a second significant population age of 249.3 ± 3.4 ka, along with a few crystal ages ranging 200-170 ka (Table 4 and Figure 13), consistent with an age within MIS 7.5 for the original beach/alluvial deposit. An age $\geq 134 \pm 3.5 \leq 198.4 \pm 7.3$ ka is established for the sampled backbeach deposit, showing that it accumulated above the MIS 7.5 paleosurface during ca. 110 ky (i.e., 245 through 134 ka). The lack of crystals deriving from the eruptions between 132 and 70 ka at the MSVD (see Figure 13), strongly suggests that the sampled layer cannot be younger. Indeed, accidental absence of crystal ages within this time span is statistically unlikely, given the eastern dispersal axis of the MSVD eruption (e.g. Sottili et al., 2004; Di Rita and Sottili, 2019) and the occurrence of large explosive eruptions 90 through 70 ka at a number of centers of the so-called "Hydromagmatic Phase" (De Rita et al., 1983; Sottili et al., 2010; Marra et al., 2019b). This fact also testifies that the depositional context progressively changed after 245 ka, consistent with continued uplift of the coast and isolation of the Colle Rotondo remnant paleo-surface, which was unaffected by deposition of water transported sediment, like that occurring in alluvial plain or beach contexts, while only eolian fallout deposits were emplaced, from then on. Since sample CR-1 occurs 90 cm below the present ground level (Figure 14c), we can infer that present elevation of 63 m is a close approximation of the MIS 7.5 paleo-surface, which is overlain by a thin eolian deposit accumulated since 245 ka (input B in Figure 14c). Indeed, it is likely that samples collected closer to the surface would yield progressively younger ages, consistent with incorporation of crystals deriving from the younger eruptions of 100 ka and 90 through 70 ka. However, the

strong anthropic disturbance of the upper 70 cm of sediment prevents any reliable analysis. Sample TML-SA from Tenuta Monte di Leva section provides further inferences on the formation process of this thin eolian cover of the paleo-surfaces.

CR3		TML-SA		CSR-SA	
Age (ka)	$\pm 2\sigma$ (ka)	Age (ka)	$\pm 2\sigma$ (ka)	Age (ka)	$\pm 2\sigma$ (ka)
134,0	$\pm 14,3$	335,5	$\pm 96,7$	263,7	$\pm 29,1$
133,4	$\pm 13,7$	287,5	$\pm 72,5$	232,3	$\pm 19,8$
140,6	$\pm 12,5$	422,9	$\pm 63,3$	542,1	$\pm 17,2$
169,7	$\pm 11,7$	189,3	$\pm 54,3$	310,1	$\pm 16,3$
127,7	$\pm 11,3$	361,0	$\pm 40,6$	805,2	$\pm 9,7$
130,9	$\pm 11,2$	557,0	$\pm 40,2$	552,1	$\pm 9,0$
131,7	$\pm 9,7$	368,2	$\pm 32,7$	240,9	$\pm 8,2$
131,0	$\pm 9,6$	165,5	$\pm 28,5$	476,6	$\pm 7,1$
392,9	$\pm 9,6$	166,6	$\pm 27,9$	246,8	$\pm 6,9$
177,6	$\pm 8,3$	151,1	$\pm 27,6$	500,8	$\pm 6,8$
198,4	$\pm 7,3$	181,7	$\pm 25,4$	625,7	$\pm 6,7$
249,9	$\pm 7,2$	171,0	$\pm 24,9$	563,1	$\pm 6,2$
169,5	$\pm 6,9$	382,2	$\pm 23,2$	244,5	$\pm 5,7$
1293,0	$\pm 6,9$	389,6	$\pm 23,0$	488,3	$\pm 5,3$
245,3	$\pm 6,6$	262,8	$\pm 22,7$	395,5	$\pm 5,0$
251,6	$\pm 6,6$	371,2	$\pm 21,5$	494,5	$\pm 4,7$
250,7	$\pm 6,5$	329,8	$\pm 20,8$	263,1	$\pm 4,6$
410,7	$\pm 6,5$	266,0	$\pm 20,0$	407,9	$\pm 4,4$
495,5	$\pm 6,5$	369,5	$\pm 20,0$	597,3	$\pm 3,7$
1289,3	$\pm 6,5$	316,8	$\pm 18,7$	508,5	$\pm 3,5$
138,3	$\pm 6,3$	372,6	$\pm 18,7$	youngest population:	
298,9	$\pm 5,6$	246,2	$\pm 17,8$	244	± 4
379,1	$\pm 5,6$	398,9	$\pm 16,2$		
407,3	$\pm 5,6$	1339,3	$\pm 15,9$		
401,4	$\pm 5,1$	351,5	$\pm 15,7$		
459,2	$\pm 5,1$	430,5	$\pm 10,9$		
375,6	$\pm 4,9$	435,7	$\pm 8,7$		
393,5	$\pm 4,8$	1328,9	$\pm 8,0$		
498,4	$\pm 4,8$	252,3	$\pm 7,1$		
403,6	$\pm 4,7$	250,0	$\pm 6,6$		
400,2	$\pm 4,6$	600,0	$\pm 6,4$		
407,8	$\pm 4,6$	216,5	$\pm 6,0$		
418,1	$\pm 4,6$	409,6	$\pm 5,9$		
446,8	$\pm 4,6$	446,4	$\pm 5,6$		
503,2	$\pm 4,1$	504,4	$\pm 5,6$		
1289,9	$\pm 3,9$	549,4	$\pm 5,4$		
421,7	$\pm 3,8$	257,6	$\pm 5,1$		
416,5	$\pm 3,5$	541,7	$\pm 5,0$		
1313,1	$\pm 3,5$	239,9	$\pm 4,7$		
youngest population:		589,3	$\pm 4,4$		
134,2	$\pm 3,5$	551,8	$\pm 4,3$		
		youngest population:			
		169	± 11		

Table 5

5.2.4 TML-SA - 98-108 paleo-surface

Much caution should be used in interpreting results for the TML-SA sample because it was collected ca. 60 cm below the ground level within the soil horizon, in which both vertic processes and anthropic disturbance might have caused incorporation of younger crystals from the uppermost portion of the stratum.

However, the age spectrum of sample TML-SA, collected on the 98-108 paleosurface, is similar to that of CR3 but yields a youngest minimum age of 169 ± 11 ka (Figure 13), evidencing a relative older age, with respect to the sample collected on the 61-67 paleosurface of Colle Rotondo.

These data suggest that the sampled sand deposit represents a sedimentary horizon that was sealed from air-fall input by 170 ka, supporting the notion that the uppermost portion of the reconstructed paleo-surfaces represents an accretionary horizon, built up mainly through accumulation of alluvially/colluvially transported and, subordinately, air-fallen material. Remarkably, also in this sample the youngest crystal population is characterized by larger associated errors (Table 5), supporting the different mean of transport for this sedimentary fraction which accumulated later, as an air-fall deposit above the underlying deposits of the alluvial plain.

The very low sedimentation rate and the limited thickness of these accretionary horizons overlying the "pristine" deposits forming the paleosurfaces, whose absolute age has been determined by $^{40}\text{Ar}/^{39}\text{Ar}$ dating on "in stratum" samples from Castel Romano and Riserva Carpineto, is consistent with the geomorphologic features of the TML and CR sectors, precluding significant alluvial/colluvial sedimentation.

5.3 The MIS 9 paleo-surface

Geomorphological, lithostratigraphic, paleo-environmental and geochronological constraints obtained for the deposits of the 71-79 m paleo-surface, and part of the 80-89 m and 98-108 m paleo-surfaces, allow the identification of these paleo-surfaces as the remnant coastal terrace of the MIS 9 highstand, tectonically dislocated (Figure 11 and 15). The subrounded morphology, the medium to coarse grain-size and the high degree of sorting of the sand deposits at Riserva Carpineto (RSC) clearly indicate that the flat sectors at elevations ranging 71-79 m a.s.l. represent remnant parts of an alluvial coastal plain, stretching NW to SE parallel to the present coastline (Figure 11 and 12a3). Crystal ages yielded by sample RSC-SA firmly constrain the formation of this coastal plain within MIS 9 (see also Figure 16). The bedded deposits of Campo di Carne (CDC), ranging from coarse sand to silty clay, are suggestive of a

coastal alluvial plain, overlain by a transgressive backbeach deposit forming a wide dune ridge system culminating at ca. 85 m a.s.l. in this area (Figure 11 and 12a3), and equivalent to that occurring in Trigoria (TRIG) at analogous elevations (Figure 11 and Figure 12a1). Evidence from the Tenuta Monte di Leva (TML) site shows that this backbeach setting homogeneously extends parallel to the paleo-coastline, but it is presently displaced to a ca. 20 m higher elevation in this sector (Figure 15). Micromorphological analysis of the concretionary layer observed in the TML indicates that this massive horizon formed in alluvial to backbeach environment characterized by a water table close to the surface, consistent with the reconstructed paleogeographic conditions, which show that it was part of the coastal plain. The geologic substrate at TML is indeed identical to that at TRIG, apart from the larger thickness of the upper, aeolian sand horizon above the concretionary layer at the latter location, consistent with a post-depositional tectonic displacement between these two sectors and limited erosion at TML.

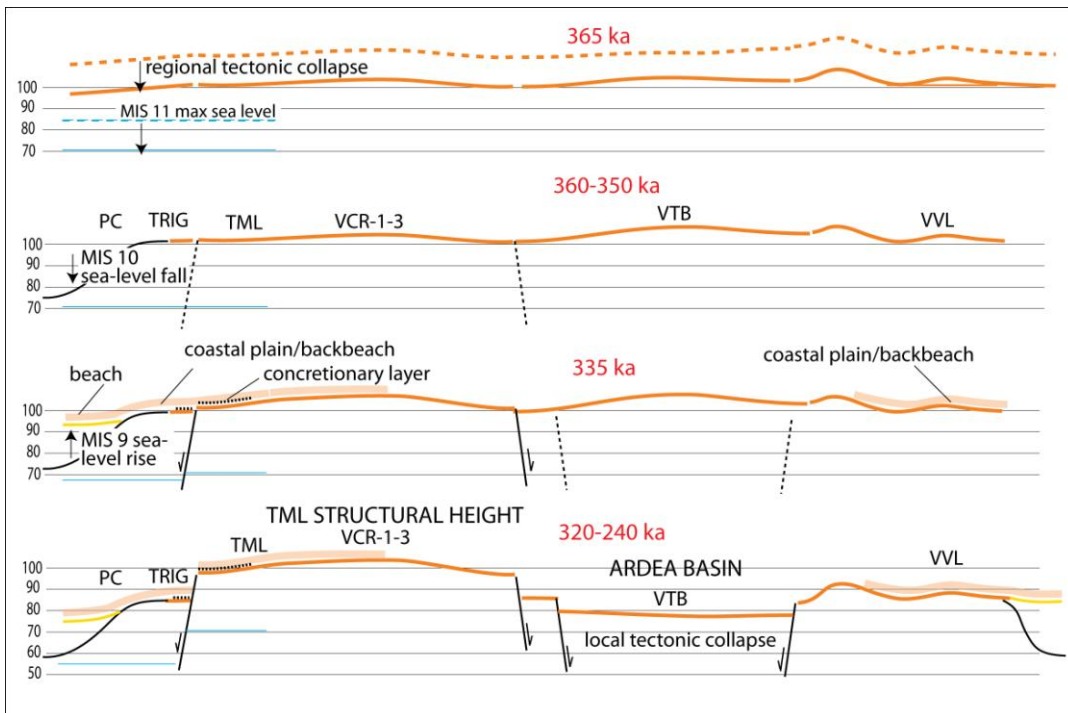


Figure 15 - Palimpsestic reconstruction of the tectonic evolution of the coastal sector between the Tiber mouth and Anzio in the time span 365 ka (age of emplacement of the Villa Senni Eruption Unit during lowstand of MIS 10) and 240 ka (onset of MIS 7.5). a) A regional collapse immediately following emplacement of the pyroclastic flow-deposit is inferred from the elevation gain between the top surface of aggradational successions of MIS 11 and MIS 9. MIS 11. b) Erosion of the original paleo-surface occurs during the lowstand of MIS 10, 360 through 350 ka. c) Fluvial and coastal incisions are filled by sediment-aggradation during glacial termination V (335 ka) at the onset of the sea-level rise during MIS 9, and a coastal

setting including a beach to backbeach and coastal plain environment forms during the MIS 9 highstand (325 ka). d) This homogeneous coastal setting is disrupted by fault displacement forming a structural high in the TML and a collapsed sector (Ardea basin) during the time span 320-240 ka (MIS 7.5 highstand) as indicated by the upper chrono-morphological constraint represented by the inner edges of MIS 7.5 coastal terrace (see text for further explanation).

On the other hand, the 98-108 m paleo-surface represents a striking geomorphological anomaly bordering the Ardea Basin to the NW (see also Figure 4), and is clearly interpretable as the result of differential uplift at the footwall of a boundary fault of the half-graben structure (Figure 11 and 15). Also the different geologic substrate that characterizes the 71-79 m paleo-surface within the Ardea Basin (e.g., VTB), which is formed by volcanic deposits (i.e.: the same substrate as the inland portion of the 98-108 m paleo-surface in VCR 1-2), is suggestive of tectonic lowering following the formation of a homogeneous coastal platform during the highstand of MIS 9, throughout this region. In contrast, in the case of a pre-existing embayment in this area, the 71-79 m paleo-surface at VTB should have had the same sedimentary substrate as that occurring in PC and RSC, confirming a coastal environment. In particular, the tectonic collapse of the Ardea Basin is constrained between 320 ka (end of the MIS 9 highstand) and 240 ka (highstand of MIS 7.5) (Figure 15), as provided by the geometry of the 60-67 m and 51-57 m coastal terraces, indicating that an embayment formed by the time of establishment of the new coastline during MIS 7.5 through MIS 7.1 (see Figure 3 and 4). Remarkably, this time span is coincident with the occurrence of the Monte delle Fate phase of activity at the Colli Albani Volcanic district (Gaeta et al., 2016, and references therein).

5.4 MIS 7.5 paleo-surface

The secure correlation with MIS 9 for the coastal plain deposits of the 71-79 m paleosurface, combined with previous geochronologic constraints that frame the 51-57m paleosurface within the broad MIS 7.5 - MIS 7.1 interval (Figure 16a), suggests that the intermediate 61-67 m surface should be correlated with the early interglacial 7.5, while the paleo-surface occurring a few meters below, at an elevation of 51-57 m, should be correlated with the later isotopic peaks 7.3/7.1 which are not separated by a marked sea-level fall (See Figure 16a), and can be regarded as a single eustatic event. Crystal age distribution yielded by sample CR3 from Colle Rotondo supports this correlation (Figure 16b). Based on the considerations reported above on the errors associated with the $^{40}\text{Ar}/^{39}\text{Ar}$ dating and their direct relation with grain-size, we can infer that an alluvial coastal plain formed by 249.3 ± 3.4 ka, an age remarkably coincident with glacial termination III at the onset of MIS 7.5 (Figure 16b), at ca.

60 m a.s.l.. It was successively mantled by a wind-blown deposit derived from the nearby beach during the interval 200 - 170 ka, a time when the coastline rebounded to the elevation of 60 m a.s.l. during sea-level high stands linked with the double peak in the isotopes curve of MIS 7.3 and 7.1. Indeed, according to geomorphologic reconstruction, sedimentologic features, and micromorphologic analysis, the Colle Rotondo sand is a backbeach deposit. The sand grains originated mainly from very proximal aeolian transport from the beach, where the original sediment accumulated after being eroded and transported by the Tiber River and its tributaries (A in Figure 14a). Moreover, since formation of the dune ridge, more aeolian material, as well as primary, air-fallen volcanic deposits (including sanidine minerals, B in Figure 14a), accumulated above it. Eventually, this sector was isolated from the coastal environment by the continued uplift, and it was affected only by deposition of the syn-eruptive fallout deposit of the Baccano unit at 132 ± 2 ka. If we consider the strong uplift of more than 50 m that occurred from 250 ka, the wind-blown depositional mechanism rapidly became ineffective, due to the increased elevation and distance from the coastline (e.g., by 125 ka, Figure 14b). The regional uplift, determining the deep incision of the coastal terrace through the action of fluvial erosion, also generated the canyon-like morphology that characterizes this area, isolating the Colle Rotondo plateau and preventing alluvial sedimentation on its top (Figure 14c-d). Therefore, it is reasonable to assume that a very limited thickness of sediment accumulated above the original paleo-surface representing the coastal terrace, mainly by the air-fall mechanism and only subordinately, as a consequence of re-mobilization of pre-existing sediment, through wind transport, or water run-off and colluviation from the upper part of the plateau towards the lower sectors (C in Figure 14b). If we consider that the elevation gain between the top and the margins of the Colle Rotondo plateau is less than 4 m (Figure 14d), the latter depositional mechanisms must have acted in a very limited way.

5.5 MIS 7.3-7.1 paleo-surface

The 51-57 m paleo-surface previously detected by Marra et al. (2016) has widespread expression at Ponte Galeria (Fig. 2), where chronostratigraphic constraints on the underlying aggradational deposits (Vitinia Formation, Luberti et al., 2017 and references therein) and their geometric/stratigraphic relationship with the 36 m terrace unambiguously provide correlation with the four-stepped sea-level rise that characterized MIS 7 (Marra et al., 2016b). In particular, an early aggradational phase of the Vitinia Formation around 269 ka matches the initial sea-level rise (A' in Fig. 16b) preceding the marked sea-level jump of glacial

termination III that occurred at 240 ka, with which in turn is associated the main aggradational succession of MIS 7.5, bracketed by post-quem ages of 253 ± 8 ka and 248 ± 4 ka (A in Fig. 16b).

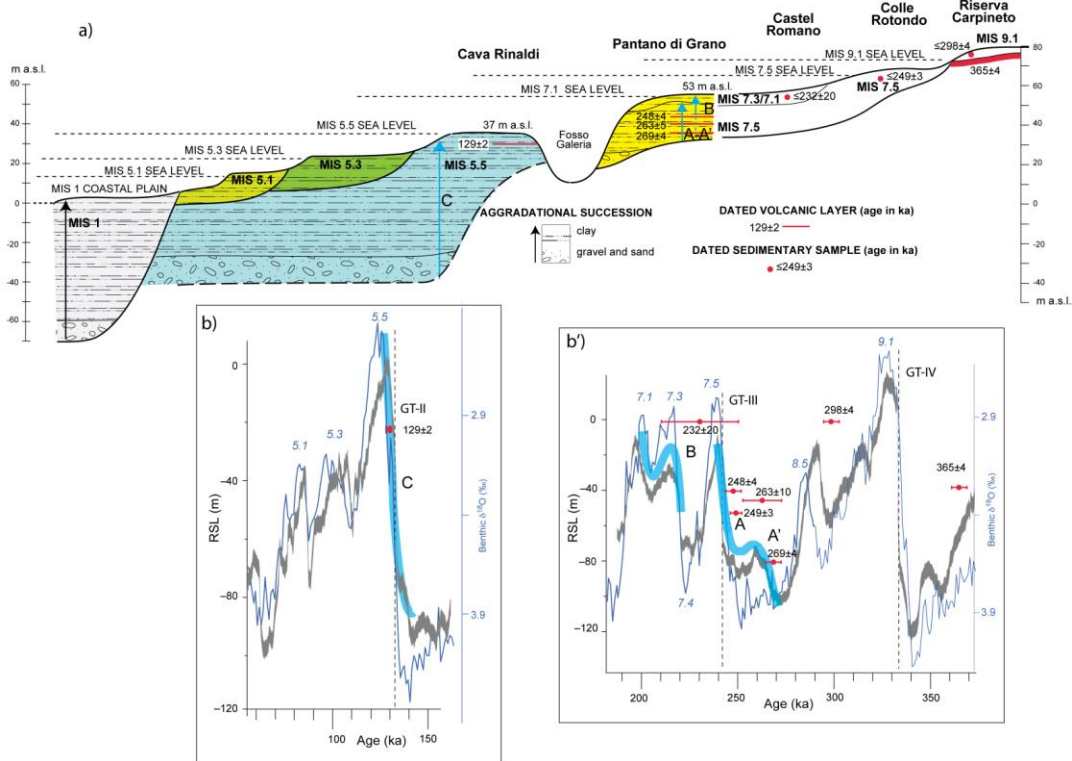


Figure 16 - a) Idealized cross-section reconstructing the terraced deposits and the corresponding aggradational successions in the investigated coastal sector, showing the geochronologic constraints providing correlation with MIS 9.1 through MIS 5.5. b-b') Ages of the dated volcanic deposits and reworked crystal populations (red dots, bars indicate the analytical error at 2σ) are compared with the Oxygen isotope curve (Lisiecki and Raymo, 2005) and the Relative Sea Level (RSL) curve (Grant et al., 2014). Correspondence of sediment aggradation with phases of rapid sea-level rise (thick blue lines) during glacial terminations (GT) is highlighted.

Finally, a marked unconformity cuts the deposits of MIS 7.5 aggradational succession and is overlain by a new aggradational succession that represents the deposit forming the flat top of the hills constituting the relict paleo-surface of 56-52 m a.s.l. The intervening erosional phase and the following sediment aggradation evidently match the sea-level fall of MIS 7.4 and the successive two-stepped sea-level rise of MIS 7.3 - MIS 7.1 (Marra et al., 2016b; B in Fig. 16b). This observation corroborates the new assessment of the 51-57 m paleo-surface, and its attribution to the later stages of MIS 7.3/7.1, rather than to MIS 7.5, as shown by correlation provided in cross-section of Figure 16a.

5.6 MIS 5.5 - 5.3 - 5.1 terraces

The occurrence of a suite of three lowest coastal terraces has been shown by geomorphologic reconstruction of their relict surfaces provided by Marra et al. (2016a, 2019a), who also demonstrated that three distinct successions of coastal plain sediments, corresponding to three coastlines at circa 34, 24 and 12 m a.s.l., are associated with these terraces (Figure 16a). The $^{40}\text{Ar}/^{39}\text{Ar}$ age of 129 ± 1 ka on a pyroclastic-flow deposit intercalated within the aggradational succession forming the 36 m terrace at Cava Rinaldi (Epi-Tyrrhenian Formation, Marra et al., 2015) demonstrated correlation with the MIS 5.5 highstand of 125 ka (Figure 16b'). The two lower terraces at 26 and 16 m were therefore tentatively correlated with the sea-level highstands of MIS 5.3 and 5.1, respectively. However, an intervening tectonic collapse of ca. 10 around 100 ka, interrupting a steady uplift phase between 250 ka and the Holocene had to be invoked by Marra et al. (2016a), in order to reconcile elevation of the terrace at 26 m with absolute sea-level established for MIS 5.3 and 5.1 in the literature (e.g. Rohling et al., 2009). A discussion of the age of these terraces is beyond the scopes of the present paper, and further geochronologic and sedimentologic investigations of these youngest successions are in progress, aimed at verifying their exact correlation with the MIS timescale. However, in the present study we have found an excellent fit of the new geomorphological and statistical assessment of these paleo-surfaces with the previous results of Marra et al. (2016a, 2019a), and we maintain preliminary correlation with the three marine isotopes' sub-stages of MIS 5.5, 5.3, and 5.1 in the discussion of the tectonic uplift.

5.7 Tectonic implications

All the sea-level markers provided by the aggradational successions of the Paleo-Tiber River correlated with MIS 21 through MIS 1 from literature and from the present study are shown in Figure 17a. Differences in elevation among the different coastal deposits assumed as sea-level markers (green shading in Figure 17a) are the result of the intervening tectonic movement (uplift or collapse) combined with the difference in maximum sea-level at each interglacial (glacio-eustatic component). This latter element is estimated assuming a sea-level 10 m lower than present during MIS 21 through MIS 15 (blue crosses in Figure 17b') based on previous literature (Marra et al., 2016 and references therein), while values estimated in Rohling et al. (2009) are considered for MIS 13 through MIS 5.1 (green crosses).

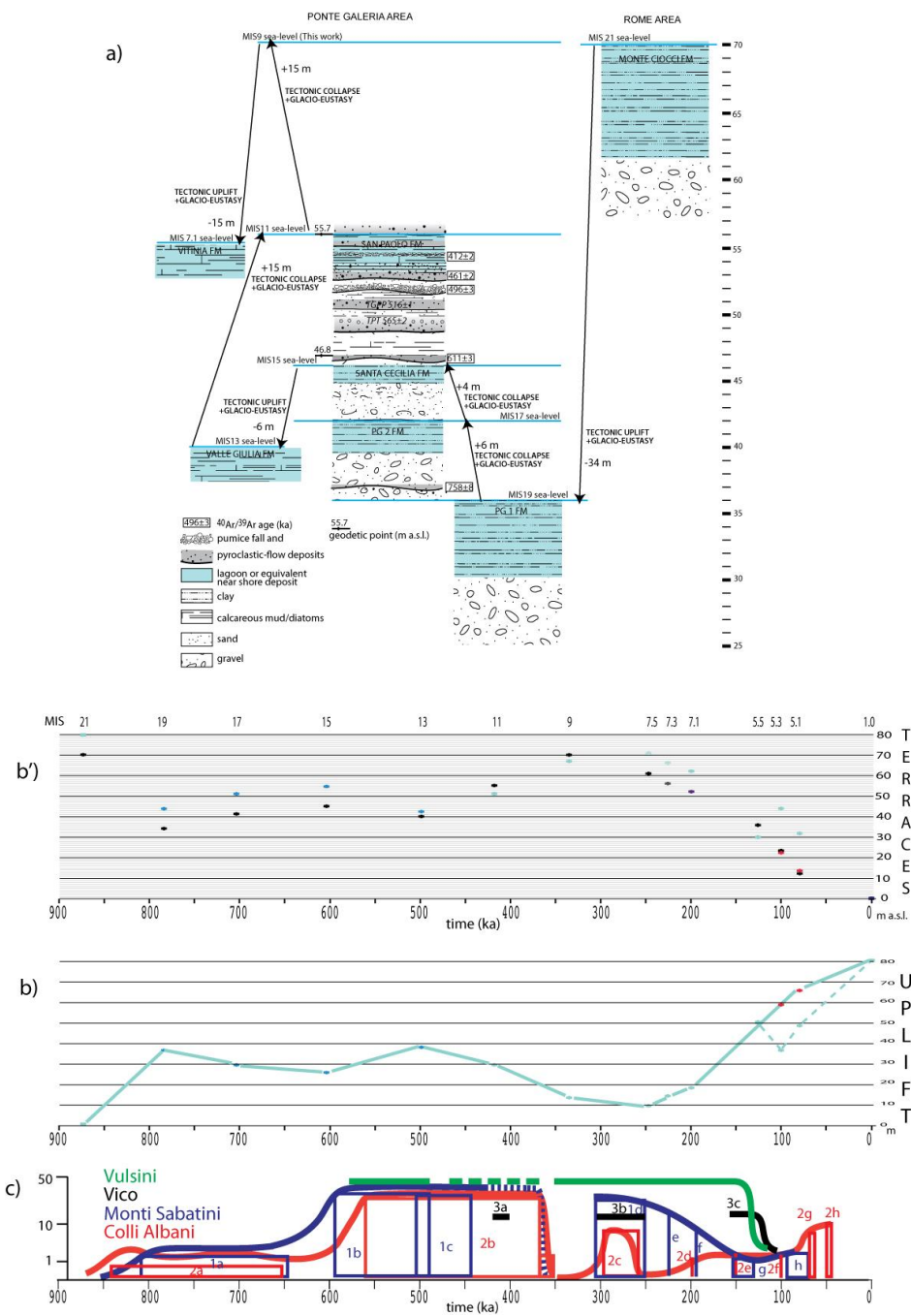


Figure 17 - a) Synoptic representation of the different sections from the Rome area indicating the aggradational successions and related sea-level indicators correlating with MIS 21 through MIS 7, integrating geochronologic and stratigraphic data from Karner and Renne, 1998; Karner and Marra, 1998; Karner et al., 2001b; Marra et al., 1998; 2016b; 2017a.

Alternative values for MIS 5.3 and 5.1 (red crosses) are also used to assess the uplift curve for the last 125 ka, based on the assumption of a more reliable uniform tectonic uplift in this time span, and on recently provided geochronologic and geomorphologic constraints on the related sea-level markers (Marra et al., 2016a, 2019a). Once the correction for the glacio-eustatic component is applied, the cumulative uplift curve of Figure 17b is obtained. Similar to previous work (Marra et al., 2016a, 2019b), comparison between the uplift curve and the eruptive histories of the volcanic districts of the Roman Province is also provided (Figure 17c). In comparison with previous reconstructions (e.g., Marra et al., 2016a) this refined uplift curve displays a marked subsidence phase between 500 and 300 ka, as provided by assessment of the MIS 9 sea-level markers at ca. 70 m a.s.l. established in the present work (Figure 17a). This fact reinforces the coupling already noted with the occurrence of two major phases of common volcanic activity at Colli Albani and Monti Sabatini 850 through 650 and 600 through 350 ka. In particular, uplift coincides with the onset of these phases, while subsidence characterizes the eruptive time spans. The subsidence phase continued until 250 ka and also encompasses the climax phase that, after a ca. 50 kyr dormancy, occurred at Vico, Monti Sabatini and Colli Albani, spanned the interval 320 - 250 ka, during which a rejuvenation of the volcanic activity occurred in all the districts of central Italy (Marra et al., 2004). The geochronologic constraints provided here for the MIS 7.5 and MIS 7.3/7.1 terraces allow a better definition of the beginning of the most recent uplift phase post-250 ka, which is characterized by an initial low gradient followed by a steady, steep increase 200 through 80 ka, and by a waning trend until the present (solid green curve in Figure 17b). As previously noted, this new uplift phase heralds and accompanies the latest volcanic phases during 90 - 70 ka at Monti Sabatini and 70-36 ka at Colli Albani, and it has been suggested to be related to the onset of a new magmatic phase extending from southern Latium to the Campanian districts of Phlegraean Fields and Vesuvius (Mara et al., 2016a). In contrast, volcanic activity seems to have been extinguished in the districts of northern Latium (Vulsini, Vico) since 100 ka. However, Marra et al. (2019a) have shown that this recent uplift phase has affected the whole coast of Latium homogeneously, in apparent conflict with the lack of a new magmatic phase at these volcanoes. In contrast, cessation of the activity at Vulsini and Vico matches the sudden tectonic collapse which is inferred when the current sea-level values for MIS 5.3 and 5.1 are assumed (dashed portion of the uplift curve in Figure 17c). However, a direct link between local volcanic activity in the northern sector and the global tectonic signal in this region is unlikely. Moreover, recent geochronologic and geomorphologic data strongly imply that anomalous sea-levels characterized the MIS 5.3 and MIS 5.1 highstands in the Mediterranean

region, suggesting the unforeseen role played by Glacial Isostatic Adjustment (GIA) on regional tectonics during the the post-glacial period (Marra et al., 2019a).

Future investigation is needed in order to understand this complex framework of vertical movement, volcanic activity and glacio-eustasy affecting the Tyrrhenian Sea Margin during the last million years. Indeed, we note that beyond the common assumption of a interconnection between subduction, volcanism and regional uplift in the back-arc domain of the central Apennines (e.g., Conticelli and Peccerillo 1992), no dedicated study aimed at evaluating the geodynamic and isostatic forces responsible for the observed tectonic uplift has been undertaken so far.

6. Conclusions

Combined geomorphologic study and statistical analysis, together with review and re-analyses of previous published data, have allowed us to identify a set of paleo-surfaces defined by discrete classes of elevation for topographic culminations in the coastal Tyrrhenian Sea sector of central Latium.

We recognized eight such paleo-surfaces defined by the elevation ranges: 98-108, 80-89, 71-79, 61-67, 51-57, 30-43, 22-27, 11-17 m a.s.l..

The three lowest paleo-surfaces are narrowly elongated parallel to the coastline and were identified through definition of the corresponding sea-level markers and geochronologic constraints in previous studies as the marine terraces of MIS 5.5, 5.3 and 5.1, (Marra et al., 2016a, 2019a).

The highest five paleo-surfaces have been investigated here and their physical extension has been validated through DEM analyses, in order to compare the results of the geomorphological study on 1:25.000 topographic maps.

The sedimentologic-stratigraphic features of the soils and of the sedimentary deposits forming these paleo-surfaces have been investigated in order to define their paleogeographic context and to identify the sea-level markers for those which have been interpreted as remnant portions of coastal terraces.

$^{40}\text{Ar}/^{39}\text{Ar}$ ages of detrital sanidine extracted from the sandy deposit of the recognized coastal terraces has allowed us to correlate the 71-79 m, the 61-67 m, and the 51-57 m paleo-surfaces with the coastal terraces formed during the MIS 9.1, MIS 7.5, and MIS 7.3/7.1 highstands, respectively.

Paleogeographic reconstruction has allowed us to interpret the 71-79 m, 80-89 m, and 98-108 m paleo-surfaces as a single tectonically displaced, widespread coastal platform formed during the MIS 9.1 highstand.

Based on the combination of our refined dataset of terrace elevations with published data on relative elevation of maximum sea level during the highstands of MIS 21 through MIS 5.1, we assess the regional uplift curve in the last 900 ka and recognize the occurrence of a climactic extensional tectonic phase affecting this coastal sector between 320 and 240 ka, coincident with occurrence of the Monte delle Fate phase of activity at the Colli albani Volcanic district.

Supplementary Material #1- 1:25.000 basemap with topographic culminations

Supplementary Material #2A: Micromorphology: Methods - Fig. S1-S6

#2B: X-Ray power diffraction methods **#2C**: SEM microphotographs - Fig. S7

Supplementary Material #2D - Diffractograms

Supplementary Material #3a, b: Full $^{40}\text{Ar}/^{39}\text{Ar}$ data.

REFERENCES

- Barberi, F., Buonasorte, G., Cioni, R., Fiordelisi, A., Foresi, L., Iaccarino, S., Laurenzi, M.A., Sbrana, A., Vernia, L., Villa, I.M., 1994. Plio-Pleistocene geological evolution of the geothermal area of Tuscany and Latium. *Mem. Descr. Carta Geol. d' It.* 49, 77-134
- Bridgland, D.R., Westaway, R., 2008. Climatically controlled river terrace staircases: a worldwide Quaternary phenomenon, *Geomorphology* 98, 285-315.
- Cioni, R., Sbrana A., Bertagnini, A., Buonasorte G., Landi, P., Rossi, U., Salvati, L., 1987. Laurenzi, M.A., Tephrostratigraphic correlations in the Vulsini, Vico and Sabatini volcanic successions. *Periodico di Mineralogia* 56, 137-155.
- Conticelli, S., Peccerillo, A., 1992. Petrology and geochemistry of potassic and ultrapotassic volcanism in central Italy: petrogenesis and inferences on the evolution of the mantle sources, *Lithos* 28, 221-240.
- De Rita, D., Funicello, R., Rossi, U., Sposato, A., 1983. Structure and evolution of the Sacrofano-Baccano caldera, Sabatini Volcanic Complex, Rome: *J. Volcanol. Geotherm. Res.* 17, 219-236.
- De Rita, D., Faccenna, C. Funicello, R. Rosa, C., 1995. Stratigraphy and volcano-tectonics, in *The Volcano of the Alban Hills*, edited by R. Trigila, Università degli Studi di Roma "La Sapienza", Roma, 33-71.
- Everdin, J.F., Curtis, G., 1965. The potassium-argon dating of Late Cenozoic rocks in East Africa and Italy. *Current Anthrop.*, 6, 343-369.
- Faccenna, C., Funicello R., Bruni A., Mattei A., Sagnotti L., 1994. Evolution of a transfer-related basin: the Ardea Basin (Latium, Central Italy). *Basin Research* 5, 12-11.
- Farr, T. G., Hensley, S., Rodriguez, E., Martin, J., Kobrick, M., 2000. The Shuttle Radar Topography Mission, *Proceedings of a Conference held 26-29 October 1999, Toulouse, France.* European Space Agency, 2000. ESA-SP vol. 450, ISBN: 9290926414, p.361.
- Ferranti, L., Antonioli, F., Mauz, B., Amorosi, A., Dai Pra, G., Mastronuzzi, G., Monaco, C., Orrù, P., Pappalardo, M., Radtke, U., Renda, P., Romano, P., Sansò, P., Verrubbi, V., 2006. Markers of the last interglacial sea-level high stand along the coast of Italy: Tectonic implications. *Quaternary International* 145/146, 30-54.
- Freda, C., Gaeta, M., Palladino, D. M., Trigila, R., 1997. The Villa Senni Eruption (Alban Hills, Central Italy): the role of H₂O and CO₂ on the magma chamber evolution and on the eruptive scenario. *Journal of Volcanology and Geothermal Research* 78, 103-120.
- Gaeta, M., Freda, C., Marra, F., Arienzo, I., Gozzi, F., Jicha, B., Di Rocco, T., 2016. Paleozoic metasomatism at the origin of Mediterranean ultrapotassic magmas: constraints inferred from time-dependent geochemistry of volcanic products from Colli Albani (Central Italy), *Lithos*, 244, 151-164. <http://dx.doi.org/10.1016/j.lithos.2015.11.034>

Gatta, M., Giaccio, B., Marra, F., Rolfo, M.F., 2017. Trace-element fingerprinting of the 69–36 ka Colli Albani eruptive units: A preliminary dataset for archaeological and tephra studies in central-southern Italy. *Journal of Archaeological Science: Reports*, 16, 330-340.

Giaccio, B., Marra, F., Hajdas, I., Karner D.B., Renne, P.R., Sposato A., 2009. $^{40}\text{Ar}/^{39}\text{Ar}$ and ^{14}C geochronology of the Albano maar deposits: implications for defining the age and eruptive style of the most recent explosive activity at the Alban Hills Volcanic District, Italy. *Journal of Volcanology and Geothermal Research* 185, 203-213.

Giaccio, B., Niespolo, E., Pereira, A., Nomade, S., Renne, P.R., Alber, P.G., Arienzo, I., Regattieri, Wagner, B., Zanchetta, G., Gaeta, M., Galli, P., Mannella, G., Peronace, E., Sottili, G., Florindo, F., Leicher, N., Marra, F., Tomlinson, E.L., 2017. First integrated tephrochronological record for the last ~190 kyr from the Fucino Quaternary lacustrine succession, central Italy. *Quaternary Science Reviews* 158, 211-234. <http://dx.doi.org/10.1016/j.quascirev.2017.01.004>

Giordano, G., De Benedetti, A.A., Diana, A., Diano, G., Gaudio, F., Marasco, F., Miceli, M., Mollo, S., Cas, R.A.F., Funiciello, R., 2006. The Colli Albani mafic caldera (Roma, Italy): stratigraphy, structure and petrology, *J. Volcanol. Geotherm. Res.*, 155, 49–80.

Grant, K.M., Rohling, E.J., Bronk Ramsey, C., Cheng, H., Edwards, R.L., Florindo, F., Heslop, D., Marra, F., Roberts, A.P., Tamisiea, M.E., Williams, F., 2014. Sea-level variability over five glacial cycles. *Nature Communications* 5, 5076. doi:10.1038/ncomms6076

Jicha, B.R., Singer, B.S., Sobol, P. 2016. Re-evaluation of the ages of $^{40}\text{Ar}/^{39}\text{Ar}$ sanidine standards and supereruptions in the western U.S. using a Noblesse multi-collector mass spectrometer. *Chemical Geology* 431, 54–66.

Karner, D.B., Marra, F., 1998. Correlation of fluviodeltaic aggradational sections with glacial climate history: A revision of the Pleistocene stratigraphy of Rome. *Geological Society of America Bulletin* 110, 748-758.

Karner, D.B., Marra, F., Florindo, F., Boschi, E., 2001a. Pulsed uplift estimated from terrace elevations in the coast of Rome: Evidence for a new phase of volcanic activity? *Earth and Planetary Science Letters* 188, 135-148.

Karner, D.B., Marra, F., Renne, P.R., 2001b. The history of the Monti Sabatini and Alban Hills volcanoes: groundwork for assessing volcanic-tectonic hazards for Rome. *J. Volc. and Geoth. Res.* 107: 185-215.

Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}\text{O}$ records. *Paleoceanography* 20, PA1003. doi:10.1029/2004PA001071.

Luberti, G.M., Marra, F., Florindo, F., 2017. A review of the stratigraphy of Rome (Italy) according to geochronologically and paleomagnetically constrained aggradational successions, glacio-eustatic forcing and volcano-tectonic processes. *Quaternary International*. <http://dx.doi.org/10.1016/j.quaint.2017.01.044>

Malinverno, A., Ryan, W.B.F., 1986. Extension in the Tyrrhenian sea and shortening in the Apennines as results of arc migration driven by sinking of the lithosphere. *Tectonics* 5, 227-245.

- Mariucci, M.T., S. Pierdominici, F. Marra, P. Montone, L. Pizzino, 2008. Looking into a volcanic area: an overview on the 350m scientific drilling at Colli Albani (Rome, Italy). *J. Volcanol. Geotherm. Res.*, doi:10.1016/j.jvolgeores.2008.04.007.
- Marra, F., Florindo, F., Boschi E., 2008. The history of glacial terminations from the Tiber River (Rome): insights to glacial forcing mechanisms, *Paleoceanography*, 23, PA2205, doi:10.1029/2007PA001543.
- Marra F., Karner, D.B., Freda, C., Gaeta, M., Renne, P.R., 2009. Large mafic eruptions at the Alban Hills Volcanic District (Central Italy): chronostratigraphy, petrography and eruptive behavior. *Journ. of Volc. and Geoth. Res.* 179, 217-232. doi:10.1016/j.jvolgeores.2008.11.009
- Marra, F., Sottili, G., Gaeta, M., Giaccio, B., Jicha, B., Masotta, M., Palladino, D.M., Deocampo, D., 2014. Major explosive activity in the Sabatini Volcanic District (central Italy) over the 800-390 ka interval: geochronological - geochemical overview and teprostratigraphic implications, *Quaternary Science Reviews* 94, 74-101.
- Marra, F., Ceruleo, P., Jicha, B., Pandolfi, L. Petronio, Salari, L. , 2015. A new age within MIS 7 for the *Homo neanderthalensis* of Saccopastore in the glacio-eustatically forced sedimentary successions of the Aniene River Valley, Rome. *Quaternary Science Reviews* 129, 260-274. doi:10.1016/j.quascirev.2015.10.027
- Marra, F., Florindo, F., Anzidei, M., Sepe, V., 2016a. Paleo-surfaces of glacio-eustatically forced aggradational successions in the coastal area of Rome: assessing interplay between tectonics and sea-level during the last ten interglacials. *Quaternary Science Review*, 148, 85-100. <http://dx.doi.org/10.1016/j.quascirev.2016.07.003>
- Marra, F., Rohling, E.J., Florindo, F., Jicha, B., Nomade, S., Pereira, A., Renne., P.R., 2016b. Independent $^{40}\text{Ar}/^{39}\text{Ar}$ and ^{14}C age constraints on the last five glacial terminations from the aggradational successions of the Tiber River, Rome (Italy). *Earth Planet Sci Lett.* in press.
- Marra, F., Gaeta, M., Giaccio, B., Jicha, B., Palladino, D., Polcari, M., Sottili, G., Taddeucci, J., Florindo, F., Stramondo, S., 2016c. Assessing the volcanic hazard for Rome: $^{40}\text{Ar}/^{39}\text{Ar}$ and In-SAR constraints on the most recent eruptive activity and present-day uplift at Colli Albani Volcanic District, *Geophys. Res. Lett.* 43, 6898-6906. doi:10.1002/2016GL069518.
- Marra, F., Florindo, F., Petronio, C., 2017. Quaternary fluvial terraces of the Tiber Valley: geochronologic and geometric constraints on the back-arc magmatism-related uplift in central Italy. *Journal Scientific Reports* 7: 2517. DOI:10.1038/s41598-017-02437-1
- Marra, F., Petronio, C., Salari, L., Florindo, F., Giaccio, B., Sottili, G., 2018a. A review of the Villafranchian fossiliferous sites of Latium in the framework of the geodynamic setting and paleogeographic evolution of the Tyrrhenian Sea margin of central Italy, *Quaternary Science Reviews* 191, 299-317. 10. 1016/ j. quascirev. 2018. 05. 011
- Marra, F., Petronio, C., Ceruleo, P., Di Stefano, G., Florindo, F., Gatta, M., La Rosa, M., Rolfo, M.F., Salari, L., 2018b. The archaeological ensemble from Campoverde (Agro Pontino, central Italy): new constraints on the Last Interglacial sea level markers. *Scientific Reports*, SREP-18-23649, DOI : 10.1038/s41598-018-36111-x

Marra F., Nomade S., Pereira A., Petronio C., Salari L., Sottili G., Bahain J.J., Boschian G., Di Stefano G., Falgueres C., Florindo F., Gaeta M., Giaccio B., Masotta M., 2018c. A review of the geologic sections and the faunal assemblages of Aurelian Mammal Age of Latium (Italy) in the light of a new chronostratigraphic framework. *Quaternary Science Reviews* 181, 173-199. doi.org/10.1016/j.quascirev.2017.12.007

Marra, F., Bahain, J.-J., Jicha, B., Nomade, S., Palladino, D.M., Pereira, A., Tolomei, C., Voinchet, P., Anzidei, M., Aureli, D., Ceruleo, P., Falguères, C., Florindo, F., Gatta, M., Ghaleb, B., La Rosa, M., Peretto, C., Petronio, C., Rocca, R., Rolfo, M.F., Salari, L., Smedile, A., Tombret, O., 2019a. Reconstruction of the MIS 5.5, 5.3 and 5.1 coastal terraces in Latium (central Italy): a re-evaluation of the sea-level history in the Mediterranean Sea during the Last Interglacial, *Quaternary International*.

Marra, F., Florindo, F., Jicha, B.R., Nomade, S., Palladino, D.M., Pereira, A., Sottili, G., Tolomei, C., 2019b. Assessing volcano-tectonic hazard of the Monti Sabatini Volcanic District on the city of Rome (central Italy): evidence from new geochronologic constraints on the Tiber River MIS 5 terraces, *Scientific Reports*, in press.

Masotta, M., Gaeta, M., Gozzi, F., Marra, F., Palladino, D.M., Sottili, G., 2010. H₂O- and temperature-zoning in magma chambers: the example of the Tufo Giallo della Via Tiberina eruptions (Sabatini Volcanic District, central Italy). *Lithos* 118, 119-130.

Nicoletti, M., 1969. Datazioni argon-potassio di alcune vulcaniti delle regioni vulcaniche Cimina e Vicana. *Per. Mineral.*, 38, 1-20.

Nisi, M.F., Antonioli, F., Dai Pra, G., Leoni, G., Silenzi S., 2003. Coastal Deformation between the Versilia and the Garigliano plains (Italy) derived from the elevations of the Last Interglacial stage, *Journal of Quaternary Science* 18, 709-721.

Palladino, D., Simej, S., Sottili, G., and Trigila, R., 2010, Integrated approach for the reconstruction of stratigraphy and geology of Quaternary volcanic terrains: An application to the Vulsini Volcanoes (central Italy), in *Stratigraphy and Geology of Volcanic Areas* (eds. G. Groppelli, and L. Viereck-Goette), *The Geological Society of America Special Paper*, 464, 63-84. doi: 10.1130/2010.2464(04).

Patacca, E., Sartori, R., Scandone, P., 1990. Tyrrhenian basin and apenninic arcs: kinematic relations since late Tortonian times. *Mem. Soc. Geol. It.* 45, 425-451.

Peccerillo, A., Frezzotti, M.L., 2015. Magmatism, mantle evolution and geodynamics at the converging plate margins of Italy. *Journal of the Geological Society*. <http://dx.doi.org/10.1144/jgs2014-085>

Pereira, A., Nomade, S., Falguères, C., Bahain, J.-J., Tombret, O., Garcia, T., Voinchet, P., Bulgarelli, A.G., Anzidei, P., 2017. 40Ar/39Ar and ESR/U- series data for the La Polledrara di Cecanibbio archaeological site (Lazio, Italy). *Journal of Archaeological Science: Reports*, in press.

Perini, G., Francalanci, L., Davidson, J.P., and Conticelli, S., 2004, Evolution and genesis of magmas from Vico volcano, Central Italy: multiple differentiation pathways and variable parental magmas, *Journal of Petrology*, **45**, 139–182.

Rivera, T.A., Storey, M., Schmitz, M.D., Crowley, J.L., 2013. Age intercalibration of $^{40}\text{Ar}/^{39}\text{Ar}$ sanidine and chemically distinct U/Pb zircon populations from the Alder Creek Rhyolite Quaternary geochronology standard. *Chemical Geology* 345, 87-98.

Rohling E.J., Grant, K., Bolshaw, M., Roberts, A.P., Siddall, M. Hemleben, Ch., Kucera, M., 2009. Antarctic temperature and global sea level closely coupled over the past five glacial cycles. *Nature Geoscience* 2, 500-504. DOI: 10.1038/NGEO557

Serri, G., Innocenti, F., Manetti, P, 1993. Geochemical and Petrological evidence of the subduction of delaminated Adriatic continental lithosphere in the genesis of the Neogene-Quaternary magmatism of Central Italy, *Tectonophysics* 223, 117-147.

Sevink, J., Di Vito, M.A., Piochi, M., Mormone, A., Van Gorp, V., Bakels, C., 2018. A rare Mid-Würmian lithoid tuff in the Agro Pontino graben (Southern Lazio, Italy) and its identification as an Albano 5-7 related distal tephra deposit (41-36 kaBP): characteristics, provenance and palaeogeographical implications. *Annals of Geophysics*, 61, 1, S109. DOI: 10.4401/ag-7534

Sottili, G., Palladino, D.M., Marra, F., Jicha, B., Karner, D.B., Renne, P., 2010. Geochronology of the most recent activity in the Sabatini Volcanic District, Roman Province, central Italy, *Journ. of Volc. and Geoth. Res.* 196, 20-30. DOI:10.1016/j.jvolgeores.2010.07.003

Sottili G., Palladino D.M., Zanon V., 2004. Plinian activity during the early eruptive history of the Sabatini Volcanic District, Central Italy. *J. Volcanol. Geotherm. Res.* 135, 361-379.

Villa, P., Pollarolo, L., Conforti, I., Marra, F., Biagioni, C., Degano, I., Lucejko, J.J., Tozzi, C., Pennacchioni, M., Zanchetta, G., Nicosia, C., Panzeri, L., Martini, M., Sibilìa, E., From Neandertals to modern humans: New data on the Uluzzian. *Plos One* 13(5): e0196786. <https://doi.org/10.1371/journal.pone.0196786>

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